Human Factors in Lighting

Third Edition

Peter R. Boyce

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To my wife, Susan, for her love and comfort

To my daughter, Anna, for her esprit and fortitude

To my son-in-law, Mick, for his help and friendship

To my grandson, Daniel, for his promise for the future

Contents

Preface

When I completed the second edition of this book in 2002, I did not expect to be writing a third edition so soon, but events have made this necessary. Over the last decade, lighting has come under increasing pressure to justify how it is currently practised, for two reasons. The first is the contribution it is believed to make to global warming. Lighting is one of the major consumers of electricity, so wherever electricity is generated through the burning of fossil fuels, lighting can be said to be contributing to the carbon burden. The second is the increased public enthusiasm for the natural environment. Light at night represents pollution for astronomers and disturbs the natural patterns of flora and fauna for biologists. Neither those concerned with global warming nor those wishing to preserve the natural environment have much interest in lighting *per se* but rather are driven by a desire to reduce the collateral damage it can cause.

The response to these pressures by those who care about lighting has been to seek ways to make lighting more effective and more efficient, to identify what lighting conditions are required to achieve the desired outcomes at minimum cost to the environment. This search has ranged from fundamentals to applications. As a result, there have been a large number of interesting developments in our understanding of how lighting and people interact. In physiology, a new photoreceptor has been discovered in the human retina. In technology, the original electric light source, the incandescent lamp, is rapidly disappearing from many parts of the world while the use of the latest, the light emitting diode, is growing by leaps and bounds. In measurement, new systems of photometry have been proposed to cover mesopic vision and new metrics have been introduced for the perception of brightness and for colour rendering. In applications, the understanding of how lighting conditions affect human performance through changes in circadian timing and motivation rather than visibility has been growing. For health, the role of exposure to light on the circadian timing system has been the subject of much study, and the impacts of such exposure for the treatment of various conditions have begun to be revealed.

This third edition has been written to provide an up-to-date and comprehensive overview of the effects of lighting on people's lives. It is only by appreciating these effects that a reasoned balance can be struck between the benefits of lighting and the consequences for the environment.

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Three people have made significant contributions to this book. My wife, Susan Boyce, has tolerated my obsession with writing and general untidiness with her usual equanimity. My son-in-law, Mick Stevens, has provided the essential technical support required to keep me in touch with modern technology. A fellow researcher, Mariana Figueiro, was kind enough to review a draft of Chapter 3 and offered valuable comments. It is a pleasure to acknowledge their contributions.

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Author

Peter Robert Boyce has spent most of his career working in the field of lighting. From 1966 to 1990, he was a research officer at the Electricity Council Research Centre, Capenhurst, England. There, he conducted research on visual fatigue, the influence of age on visual performance, visual problems associated with viewing computer screens, hue discrimination, safe lighting for emergency conditions and security lighting. From 1990 to 2004, he was head of human factors at the Lighting Research Center, Rensselaer Polytechnic Institute, New York. There, he conducted research on visual performance, visual comfort, circadian effects, emergency lighting, perceptions of safety and lighting for driving. He also directed lighting evaluations and product testing. In addition, he taught classes in the master of science in lighting program and advised many students on their thesis work. He is a recognized authority on the interaction of people and lighting, being the author of many papers and a frequent contributor to guidance documents. Since 2008, he has been technical editor of the journal *Lighting Research and Technology.*

Section I

Fundamentals

1 Light

1.1 INTRODUCTION

This book is concerned with the interaction of people and light. To fully understand this interaction, it is first necessary to understand what light is, how its characteristics can be quantified and how it is produced and controlled. These topics are the subject of this chapter.

1.2 LIGHT AND RADIATION

To the physicist, light is simply part of the electromagnetic spectrum that stretches from cosmic rays with wavelengths of the order of femtometres to radio waves with wavelengths of the order of kilometres (Figure 1.1). What distinguishes the wavelength region between 380 and 780 nm from the rest of the electromagnetic spectrum is the response of the human visual system. Visual photoreceptors in the human eye absorb energy in this wavelength range and thereby initiate the process of seeing. Other creatures are sensitive to different parts of the electromagnetic spectrum, but light is defined by the visual response of humans.

Unfortunately for simplicity, the response of the human visual system is not the same at all wavelengths in the range 380–780 nm. This makes it impossible to adopt the radiometric quantities conventionally used to measure the characteristics of the electromagnetic spectrum for quantifying light. Rather, a special set of quantities has to be derived from the radiometric quantities by weighting them by the spectral sensitivity of the human visual system.

The principle used for the measurement of the human spectral sensitivity is the equivalence of visual effect, the effect in question being the perception of brightness. Radiation consisting of a single wavelength somewhere between 380 and 780 nm will be seen as having both a brightness and a colour. An observer viewing two equal-size visual fields presented for the same time, and with the same single wavelength and the same radiance, will consider the two fields indistinguishable, that is, equal in all respects, so they have the same visual effect. If the two fields have the same wavelength but different radiances, the field with the higher radiance will be perceived to be brighter. When both the wavelength and the radiance of the two fields are different, the two fields will be seen to differ in brightness and colour. In this situation, it is possible to achieve brightness equivalence by altering the radiance of one field until the two fields look equally bright. If R_1 and R_2 are,

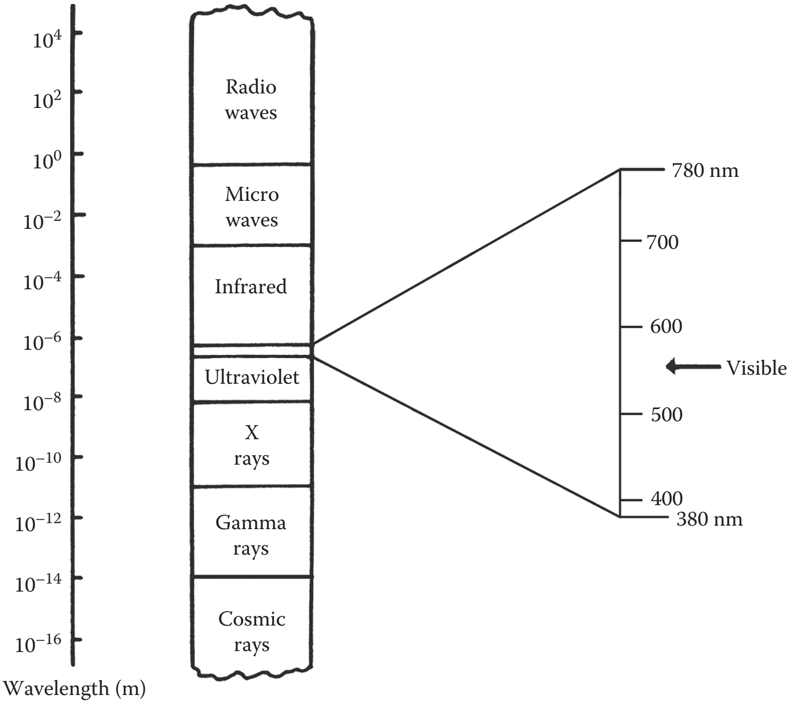

FIGURE 1.1 A schematic diagram of the electromagnetic spectrum showing the location of the visible spectrum. The divisions between the different types of electromagnetic radiation are indicative only.

respectively, the radiances of the two fields at wavelengths λ_1 and λ_2, brightness equivalence can be represented by the equation

$$V_1R_1 = V_2R_2$$

where V_1 and V_2 are the weighting factors necessary to make the equation correct for the measured radiances. Since the only measured values are radiances, each brightness equivalence match produces a ratio V_1/V_2. By establishing brightness equivalences for many pairs of wavelengths and using the transitive principle of mathematics, that is, $V_1/V_3 = (V_1/V_2) \times (V_2/V_3)$, it is possible to express the sensitivity of the visual system at each wavelength relative to its sensitivity at an arbitrarily chosen standard wavelength, that is, $V_\lambda/V_{standard}$. The standard wavelength usually chosen is the one for which human visual sensitivity is a maximum, that is, the wavelength at which, for a constant radiance, the brightness is the greatest. Then, by giving $V_{standard}$ a value of unity and plotting the resulting V_λ against wavelength, a curve can be produced which quantifies the relative efficiency of different wavelengths in producing the same perception of brightness. Such a curve is the relative spectral sensitivity curve of the human visual system. It contains the information necessary to convert the fundamental radiometric quantities into quantities suitable for measuring light.

1.3 CIE STANDARD OBSERVERS

Unfortunately, a unique relative spectral sensitivity curve applicable to all people in all conditions does not and cannot exist. Different relative spectral sensitivity curves are obtained depending on the method used for measuring brightness equivalence, on what visual photoreceptors are stimulated and on what channel of the visual system is being accessed (Kaiser, 1981). Further details of these matters are given in Chapter 2. For the moment, it is sufficient to know that the human retina has two classes of visual photoreceptors, one class operating when light is plentiful, in what are called photopic conditions (cone photoreceptors), and the other operating when light is very limited, in what are called scotopic conditions (rod photoreceptors). These two photoreceptor types have very different relative spectral sensitivities. What these spectral sensitivities are has been the subject of international agreement. The body that organizes these agreements is the Commission Internationale de l'Eclairage (CIE). In 1924, the CIE adopted the CIE standard photopic observer, based on the work of Gibson and Tyndall (1923), who took data from several experiments and proposed a smooth and symmetric spectral sensitivity curve (Viikari et al., 2005). The experiments from which the data were taken used small test fields, usually less than 2° in diameter, and the amount of light was sufficient to put the visual system into the photopic state. A later work by Judd (1951) showed that the CIE standard photopic observer was too insensitive at short wavelengths, a result which eventually led the CIE to formally recognize a modified photopic spectral sensitivity curve (CIE, 1990) with greater sensitivity than the CIE standard photopic observer at wavelengths below 460 nm. This CIE modified photopic observer was stated to be a supplement to the CIE standard photopic observer, not a replacement for it. As a result, the CIE standard photopic observer has continued to be widely used by the lighting industry. This is acceptable because the modified sensitivity at wavelengths below 460 nm has been shown to make little difference to the photometric properties of nominally white light sources that emit radiation over a wide range of wavelengths. It is only for light sources that emit significant amounts of radiation below 460 nm that changing from the CIE standard photopic observer to the CIE modified photopic observer can be expected to make a significant difference to measured photometric properties (CIE, 1978). Some coloured signals, coloured displays and narrowband light sources, such as blue light-emitting diodes (LEDs), fall into this category.

In 1951, the CIE adopted the CIE standard scotopic observer, based on measurements by Wald (1945) and Crawford (1949) using an area covering the central 20° of the visual field with a photopic luminance of approximately 0.00003 cd/m^2. While this is scientifically interesting because it represents the spectral response of the rod photoreceptors, until recently, it was rarely used by the lighting industry because the provision of almost any lighting installation worthy of the name will take the human visual system out of the scotopic state. However, the interest in mesopic vision (see Section 1.5), where both rod and cone photoreceptors are active, has increased the value of knowing how well a given light source will stimulate both types of visual photoreceptor. As a result, both the CIE standard photopic

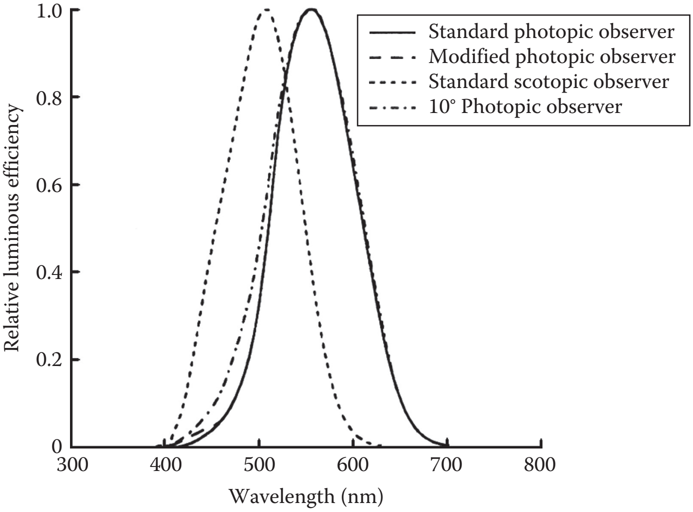

FIGURE 1.2 The relative luminous efficiency functions for the CIE standard photopic observer, the CIE modified photopic observer, the CIE standard scotopic observer and the CIE 10° photopic photometric observer.

and standard scotopic observers have become more widely used by light source manufacturers of late (see Section 1.6.4.5).

The CIE standard and modified photopic observers and the CIE standard scotopic observer are shown in Figure 1.2, the standard and modified photopic observers having maximum sensitivities at 555 nm and the standard scotopic observer having a maximum sensitivity at 507 nm (CIE, 1983, 1990). These relative spectral sensitivity curves are formally known as the 1924 CIE spectral luminous efficiency function for photopic vision, the CIE 1988 modified two-degree spectral luminous efficiency function for photopic vision and the 1951 CIE spectral luminous efficiency function for scotopic vision, respectively. More commonly, they are known as the CIE $V(\lambda)$, CIE $V_M(\lambda)$ and the CIE $V'(\lambda)$ curves. These curves are the basis of the conversion from radiometric quantities to photometric quantities, the quantities used to characterize light.

1.4 PHOTOMETRIC QUANTITIES

The most fundamental measure of the electromagnetic radiation emitted by a source is its radiant flux. This is a measure of the rate of flow of energy emitted and is measured in watts. The most fundamental quantity used to measure light is luminous flux. Luminous flux is radiant flux multiplied, wavelength by wavelength, by the relative spectral sensitivity of the human visual system, over the wavelength range 380–780 nm. This process can be represented by the equation

$$F = K_m SY_l V_l Dl$$

where

Φ is the luminous flux (lumens)
Ψ_λ is the radiant flux in a small wavelength interval $\Delta\lambda$ (watts)
V_λ is the spectral luminous efficiency function for the conditions
K_m is a constant (lumens/watt)

In Systeme Internationale (SI) units, the radiant flux is measured in watts and the luminous flux in lumens. The value of K_m is 683 lm/W for the CIE standard and modified photopic observers and 1700 lm/W for the CIE standard scotopic observer. These numbers arise from the decision of the CIE that 1 W of radiant flux at 555 nm should produce 683 lm, for both photopic and scotopic conditions. As 555 nm is the maximum sensitivity of the CIE standard and modified photopic observers, the constant is unchanged for the photopic condition. But for the CIE standard scotopic observer, the relative spectral sensitivity is only 0.402 at 555 nm. Therefore, the constant for scotopic conditions is 1700 lm/W. It is always important to identify which of the standard observers is being used in any particular measurement or calculation. This requirement has led the CIE to recommend that whenever the standard scotopic observer is being used, the word scotopic should precede the measured quantity, that is, scotopic luminous flux.

Luminous flux is used to quantify the total light output of a light source in all directions. While this is important, for lighting practice, it is also important to be able to quantify the luminous flux emitted in a given direction. The measure that quantifies this concept is luminous intensity. Luminous intensity is the luminous flux emitted per unit solid angle, in a specified direction. The unit of measurement is the candela, which is equivalent to one lumen per steradian. Luminous intensity is used to quantify the distribution of light from a luminaire.

Both luminous flux and luminous intensity have area measures associated with them. The luminous flux falling on a unit area of a surface is called the illuminance. The unit of measurement of illuminance is the lumens/square metre or lux. The luminous intensity emitted per unit projected area of a source in a given direction is the luminance. The unit of measurement of luminance is candelas/square metre. The illuminance incident on a surface is the most widely used electric lighting design criterion. The luminance of a surface is a correlate of its brightness. Table 1.1 summarizes these photometric quantities.

As might be expected, there is a relationship between the amount of light incident on a surface and the amount of light reflected from the same surface. The nature of the relationship depends on the characteristics of the reflecting surface. For a perfectly diffusely reflecting surface, the relationship is give by the equation

$$\text{Luminance} = \frac{\text{Illuminance ¥ Reflectance}}{p}$$

where

Luminance is expressed in candelas/square metre
Illuminance is expressed in lumens/square metre

For a diffusely reflecting surface, reflectance is defined as the ratio of the reflected luminous flux to the incident luminous flux. For a non-diffusely reflecting

TABLE 1.1
Photometric Quantities

Measure	Definition	Units
Luminous flux	The quantity of radiant flux which expresses its capacity to produce visual sensation	Lumens (lm)
Luminous intensity	The luminous flux emitted in a very narrow cone containing the given direction divided by the solid angle of the cone, that is, luminous flux/unit solid angle	Candela (cd)
Illuminance	The luminous flux/unit area at a point on a surface	Lumen/metre^2
Luminance	The luminous flux emitted in a given direction divided by the product of the projected area of the source element perpendicular to the direction and the solid angle containing that direction, that is, luminous intensity/unit area	Candela/metre^2
Reflectance	The ratio of the luminous flux reflected from a surface to the luminous flux incident on it	
For a diffusely reflecting surface	Luminance = (Illuminance × Reflectance)/π	
Luminance factor	The ratio of the luminance of a reflecting surface viewed from a given direction to that of a perfect white uniformly diffusing surface identically illuminated	
For a non-diffusely reflecting surface, for a specific direction and lighting geometry	Luminance = (Illuminance × Luminance factor)/π	

surface, that is, a surface with some specularity, the same equation between luminance and illuminance applies but reflectance is replaced with luminance factor. Luminance factor is defined as the ratio of the luminance of the surface viewed from a specific position and lit in a specified way to the luminance of a perfect white diffusely reflecting surface viewed from the same direction and lit in the same way. It should be clear from this definition that a non-diffusely reflecting surface can have many different values of the luminance factor. Table 1.1 summarizes these definitions.

Unfortunately for consistency, photometry has a long history that has generated a number of different units of measurement for illuminance and luminance. Table 1.2 lists some of the alternative units, together with the multiplying factors necessary to convert from the alternative unit to lumens/square metre for illuminance and candelas/square metre for luminance.

Both illuminance and luminance are widely used in lighting practice to quantify the end result of installing a lighting system and the stimulus to the visual system. Being able to define these quantities is useful, but in addition, it is always helpful to have an idea of what are representative magnitudes for these quantities in different situations. Table 1.3 shows some illuminances and luminances typical of commonly occurring situations, all measured using the CIE standard photopic observer.

TABLE 1.2
Some Photometric Units of Measurement for Illuminance and Luminance and the Multiplying Factors Necessary to Change Them to SI Units

Quantity	Unit	Dimensions	Multiplying Factor
Illuminance	Lux	Lumen/metre^2	1.00
	Metre candle	Lumen/metre^2	1.00
	Phot	Lumen/centimetre^2	10,000
	Foot candle	Lumen/foot^2	10.76
Luminance	Nit	Candela/metre^2	1.00
	Stilb	Candela/centimetre^2	10,000
		Candela/inch^2	1,550
		Candela/foot^2	10.76

TABLE 1.3
Typical Illuminance and Luminance Values

Situation	Illuminance (lm/m^2)	Typical Surface	Luminance (cd/m^2)
Clear sky in summer in temperate zones	100,000	Grass	3,200
Overcast sky in summer in temperate zones	16,000	Grass	500
Textile inspection	1,500	Light grey cloth	140
Office work	500	White paper	120
Heavy engineering	300	Steel	20
Good road lighting	10	Concrete road surface	1.0
Moonlight	0.5	Asphalt road surface	0.01

There are other photometric quantities used in lighting design which lie outside the SI. One is luminous exitance (Cuttle, 2010). For a perfectly diffusely reflecting surface, the luminous exitance is the product of the illuminance falling on the surface and the reflectance of the surface. Luminous exitance is usually measured in lumens/square metre, but it can be found measured in lumens/square foot or footlamberts. Unlike luminance, luminous exitance provides no information about the direction in which the light is emitted.

Two others are 3D measures of illuminance: cylindrical illuminance and scalar illuminance. Illuminance as defined in the SI is the luminous flux density at a point on a plane. This is useful for quantifying the amount of light falling on a desk or on the eye, but it is of little value for describing the amount of light falling on a 3D object. Cylindrical illuminance is the average illuminance falling on the vertical surface of a small cylinder located at a point in space. Scalar illuminance is the average illuminance falling on the surface of a small sphere located at a point in space. These measures can be used to quantify how much light will fall on a 3D object in a space, such as a pedestrian walking down the street or a display in a museum.

While cylindrical and scalar illuminances are of value, they are still simply averages, so they tell us a very limited amount about how the object will appear. For this, another measure is needed, the vector illuminance. Like all vectors, this has two elements, a magnitude and a direction. The magnitude of the vector is the maximum difference between the two sides of a plane passing through a point in space, while the direction is the normal to the plane in which the maximum difference occurs. Vector illuminances give an indication of how strongly and in which direction light appears to flow across a space, for example, from a window (Lynes et al., 1966). When combined with the scalar illuminance to form the vector/scalar ratio, it is possible to gain an understanding of how strong and in what location, highlights and shadows are likely to form on objects of different forms (Cuttle, 2008). The role of these metrics in perception is discussed in Chapter 6.

1.5 SOME LIMITATIONS

Although the photopic photometric quantities defined earlier can be calculated or measured precisely, it is important to appreciate that they only represent the visual effect of light in a particular state. Specifically, they represent the brightness response of the central 2° of the retina, that is, the fovea, in high light level conditions. Changing the location, field size or light level of the stimulus can change the spectral sensitivity of the visual system.

Moving a 2° stimulus away from the fovea into the periphery of the retina changes the spectral sensitivity to one with much greater sensitivity at the short-wavelength end of the visible spectrum, unlike any of the CIE standard observers (Weale, 1953). This phenomenon is not incorporated into any system of photometry because it is considered of little practical interest. As discussed in Chapter 2, it is the fovea that is physiologically designed for examination of detail, the peripheral visual field being essential for identifying where the fovea should be directed.

The effect of the field size was recognized by the CIE in 1964 when a provisional relative spectral sensitivity curve for the central 10° of the visual field in photopic conditions was approved (CIE, 1986, see Figure 1.2), a process that culminated in the formal adoption of the 10° photopic photometric observer (CIE, 2005). This observer shows greater sensitivity to short-wavelength light than the CIE standard photopic observer because the visual field extends beyond the macula, an area covering the central 5° of the retina and containing a pigment that attenuates short-wavelength light and into the area where many more short-wavelength cone photoreceptors are found.

As for the effect of changing light level, it should be appreciated that there is a large gap in the luminance range between photopic and scotopic conditions (see Section 2.3.2). This gap is called the mesopic condition where both rod and cone photoreceptors are active. For the fovea, the CIE standard photopic observer still applies in the mesopic range because there are only medium- and long-wavelength cones present in the fovea, which is what the CIE standard photopic observer is based on. However, in the rest of the visual field, the spectral sensitivity is in a state of continual change as the balance between rod and cone photoreceptors changes with light level until either rods dominate, as in scotopic vision, or cones dominate, as in photopic vision. It must be emphasized that there is no such thing as a single standard mesopic observer. This is because the exact spectral sensitivity in the mesopic range depends on the light level to which the visual system is adapted. Two systematic attempts have been made to develop a mesopic system of photometry, one using reaction times to achromatic stimuli (Rea et al., 2004a) and the other using performance on a variety of visual activities likely to occur during nighttime driving involving both achromatic and chromatic information (Goodman et al., 2007). The CIE has tested both these models with independent data and derived a compromise model that provides a smooth transition in spectral sensitivity between the standard photopic observer at 5 cd/m^2 and the standard scotopic observer at 0.005 cd/m^2 (CIE, 2010a). This model allows a given photopic luminance to be converted to a mesopic luminance provided the scotopic/photopic ratio of the lighting is known (see Section 1.6.4.5).

It is to be hoped that the CIE system of mesopic photometry soon becomes widely adopted for exterior lighting (Kostic and Djokic, 2012). This is desirable because much exterior lighting provides conditions that are in the mesopic range, but, at the moment, all the photometric quantities that are used to characterize exterior lighting are based on the CIE standard photopic observer. This practice can lead to situations where the photometric measurements bear little relation to the visual effect of the lighting. The use of the CIE system of mesopic photometry will go some way to reduce such disturbing observations.

Two other systematic effects that lead to different relative spectral sensitivities from the values represented by the CIE standard photopic observer occur with age or with defective colour vision. As discussed in Section 13.2, as the eye ages, the transmittance of the lens decreases, particularly at the short-wavelength end of the visible spectrum. This will lead to a reduced sensitivity in this wavelength region for older people (Sagawa and Takahashi, 2001). For people with defective colour vision, either there are missing photopigments or the photopigments are different from the normal (see Section 2.2.7). In either case, the relative spectral sensitivity of such people is likely to depart from that of the CIE standard photopic observer.

In addition to these systematic effects, there are the inevitable individual differences between people. Figure 1.3 shows the range of relative spectral sensitivity for 52 observers, taken from the data of Gibson and Tyndall (1923), from which the CIE standard photopic observer was derived. Clearly, there are wide individual differences in spectral sensitivity. This implies that the fact that the photometric quantities can be calculated and/or measured precisely is no guarantee that they will be closely related to the visual effects produced. Despite this limitation, the two CIE standard observers and the CIE system of mesopic photometry have a definite value. They provide a globally agreed means for the lighting industry to quantify the performance of its products, in terms of luminous flux and luminous intensity distributions, and for designers to quantify what their lighting systems deliver, in terms of illuminance and luminance. Despite the utility of such measures, whenever considering the photometric quantities for

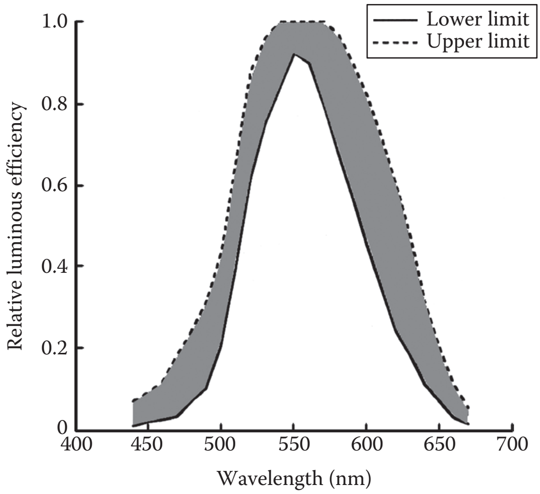

FIGURE 1.3 The range of relative luminous efficiency functions for 52 observers. The results for all the observers fall in the shaded area. (After Judd, D.B. and Wyszecki, G.W., *Colour in Business, Science and Industry*, John Wiley & Sons, New York, 1963.)

a given lighting situation, it is always important to ask if the photometric quantity is appropriate to the situation. If it is not, then the apparent precision of the quantity may be misleading.

1.6 COLORIMETRIC QUANTITIES

The photometric quantities described earlier do not take into account the wavelength combination of the light received at the eye. Thus, it is possible for two luminous fields to have the same luminance but to be made up of totally different combinations of wavelengths. In this situation, and provided either photopic or mesopic conditions prevail, the two fields may look different in colour. Exactly what colour will be seen depends not only on the spectral distribution of the radiation incident on the retina but also on several other factors, such as the luminance and the colour or colours of the surroundings and the state of adaptation of the observer (Purves and Beau Lotto, 2003). Colour is a perception developed in the brain from past experience and the information contained in the retinal image. Light itself is not coloured. Nonetheless, to have a means of characterizing the colour perception associated with different light sources and other stimuli to the visual system, some way had to be found to provide a quantitative measure of colour. The CIE colorimetry system provides such a measure (CIE, 2004a).

1.6.1 CIE Colorimetry System

The basis of the CIE colorimetry system is colour matching. Colour matching measurements are another example of visual equivalence in the sense that the observer is simply asked to determine whether two fields are of the same colour. From extensive colour matching measurements, the CIE colour matching functions have been determined. These functions are essentially the relative spectral sensitivity curves of human observers with normal colour vision and can be considered as another form of standard observer. There are three colour matching functions, as might be expected from the fact that humans with normal colour vision can match any colour of light with a combination of not more than three wavelengths of light from the long-, medium- and short-wavelength regions of the visible spectrum. Although the existence of three colour matching functions is analogous to the existence of the three cone photoreceptor types involved in colour vision (see Section 2.2.7), it must be emphasized that the CIE colour matching functions are not based on physiology. They are mathematical constructs that reflect the relative spectral sensitivities required to ensure that all the spectral distributions that are seen as the same colour have the same position in the CIE colorimetry system and that every spectral distribution that is seen as a different colour occupies a different position. Figure 1.4 shows two sets of colour matching functions, the 1931 standard observer for a 2° field and the CIE 10° observer. The CIE 1931 standard observer is used for colours occupying visual fields from 1° to 4° of angular subtense. The CIE 10° observer is used for colours covering visual fields greater than 4° in angular subtense, although Hu and Houser (2006) have developed colour matching functions for even larger field sizes. The values of the colour matching functions at different wavelengths are known as the spectral tristimulus values.

The colour of a light source can be represented mathematically by multiplying the spectral power distribution of the light source, wavelength by wavelength, by each of the three colour matching functions $x(\lambda)$, $y(\lambda)$ and $z(\lambda)$, the outcome being the

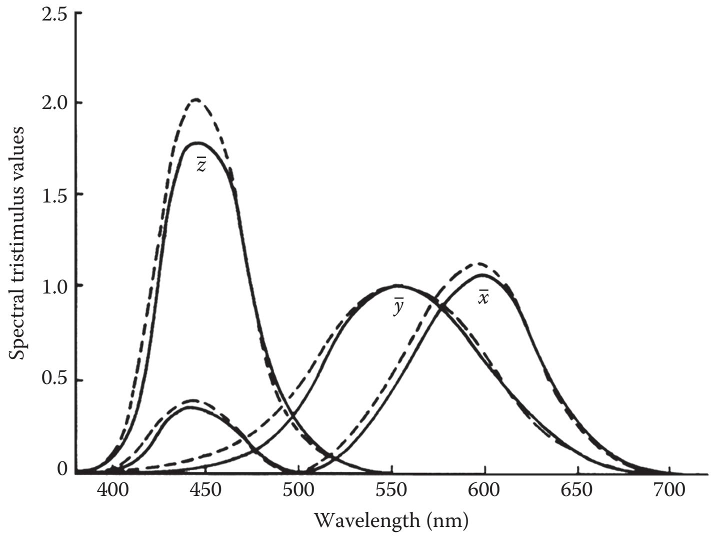

FIGURE 1.4 Two sets of colour matching functions: the CIE 1931 standard observer (2°) (solid line) and the CIE 1964 standard observer (10°) (dashed line).

amounts of three imaginary primary colours *X*, *Y* and *Z* required to match the light source colour. In the form of equations, *X*, *Y* and *Z* are given by

$$X = h\sum S(\lambda)\cdot x(\lambda)\cdot\Delta\lambda$$

$$Y = h\sum S(\lambda)\cdot y(\lambda)\cdot\Delta\lambda$$

$$Z = h\sum S(\lambda)\cdot z(\lambda)\cdot\Delta\lambda$$

where

$S(\lambda)$ is the spectral radiant flux of the light source (W/nm)

$x(\lambda)$, $y(\lambda)$, $z(\lambda)$ are the spectral tristimulus values from the appropriate colour matching function

$\Delta\lambda$ is the wavelength interval (nm)

h is an arbitrary constant

If only relative values of *X*, *Y* and *Z* are required, an appropriate value of *h* is one that makes $Y = 100$. If absolute values of *X*, *Y* and *Z* are required, it is convenient to take $h = 683$ since the value of *Y* is then the luminous flux in lumens.

If the colour being calculated is for light reflected from a surface or transmitted through a material, the spectral reflectance or spectral transmittance is included as a multiplier in the earlier equations. For a reflecting surface, an appropriate value of *h* is one that makes $Y = 100$ for a reference white because then the actual value of *Y* is the percentage reflectance of the surface.

Having obtained the *X*, *Y* and *Z* values, the next step is to express their individual values as proportions of their sum, that is,

$$x = \frac{X}{X+Y+Z} \quad y = \frac{Y}{X+Y+Z} \quad z = \frac{Z}{X+Y+Z}$$

The values *x*, *y* and *z* are known as the CIE chromaticity coordinates. As $x + y + z = 1$, only two of the coordinates are required to define the chromaticity of a colour. By convention, the *x* and *y* coordinates are used. Given that a colour can be represented by two coordinates, then all colours can be represented on a 2D surface. Figure 1.5 shows the CIE 1931 chromaticity diagram, the two axes being the *x* and *y* chromaticity coordinates. It is possible to identify a number of interesting features on the CIE 1931 chromaticity diagram. The outer curved boundary is called the spectrum locus. All pure colours, that is, those that consist of a single wavelength, lie on this curve. The straight line joining the ends of the spectrum locus is the purple boundary and is the locus of the most saturated purples obtainable. At the centre of the diagram is a point called the equal energy point. This is the point where a colourless surface will be located. Close to the equal energy point is a curve called the Planckian locus. This curve passes through the chromaticity coordinates of objects that operate as a black body, that is, the spectral power distribution of the light source is determined solely by its temperature.

The CIE 1931 chromaticity diagram can be considered as a primitive, 2D map of the relative location of colours. The saturation of a colour increases as the chromaticity coordinates get closer to the spectrum locus and further from the equal energy point. The hue

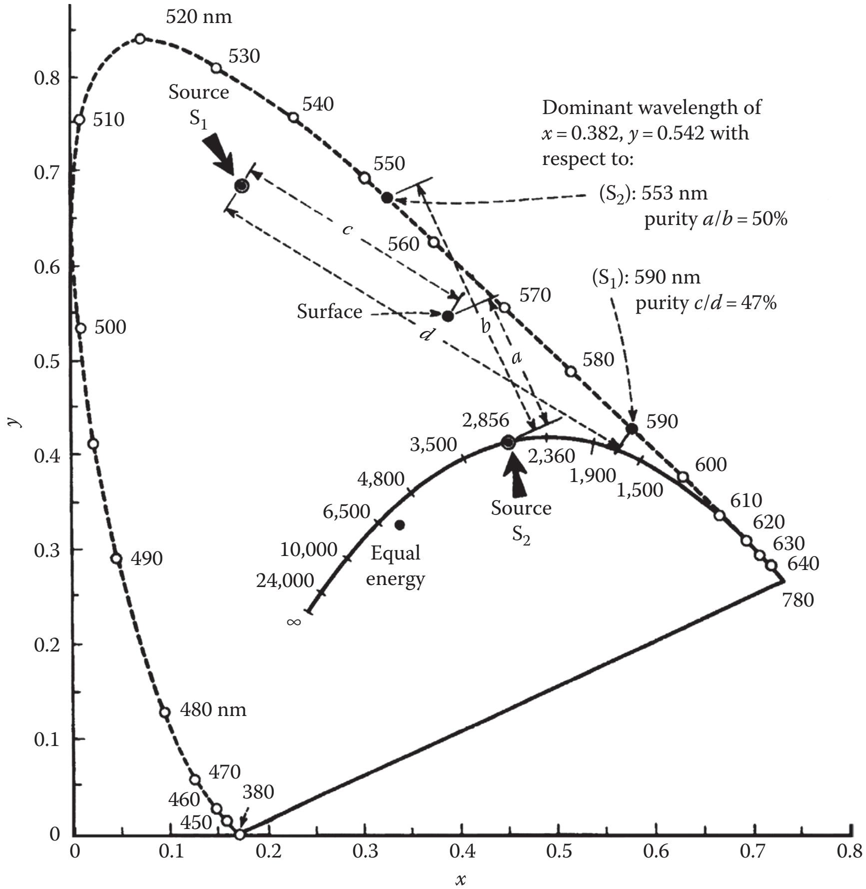

FIGURE 1.5 The CIE 1931 chromaticity diagram showing the spectrum locus, the Planckian locus, the equal energy point and the method of calculating dominant wavelength and excitation purity for a surface and two different light sources. (From Illuminating Engineering Society of North America (IESNA), *The Lighting Handbook*, 9th edn., IESNA, New York, 2000a.)

of the colour is determined by the direction in which the chromaticity coordinates move. These characteristics have been formalized as dominant wavelength and excitation purity. To determine the dominant wavelength of a surface lit by a known light source, a line is drawn through the two points represented by the chromaticity coordinates of the light source alone and the surface when lit by the light source and extended to the spectrum locus. The wavelength at which the extended line intersects the spectrum locus is the dominant wavelength. As for excitation purity, this is the ratio of the distance from the chromaticity coordinates of the light source to the chromaticity coordinates of the lit surface, divided by the total distance from the light source alone to the intersection of the line with the spectrum locus. Two examples of such calculations are shown in Figure 1.5.

Strictly, any discussion as to how a specific combination of wavelengths will appear, based on the chromaticity diagram, is nonsense. The only thing that a set of chromaticity coordinates tells us about a colour is that colours with the same chromaticity coordinates will match. They tell us nothing about the appearance of the matched colours. But this is an argument for colour vision zealots. The fact is that a red surface lit by a nominally white light source will always plot in one part of the diagram and a green in another part and so on. Thus, although the CIE 1931 chromaticity diagram is not theoretically pure, it is useful for indicating approximately how a colour will appear, a value recognized by the CIE when it specified chromaticity coordinate limits for signal lights and surfaces so that they will be recognized as red, green, yellow and blue (CIE, 1994a, 2001).

Given that different colours plot at different positions on the CIE 1931 chromaticity diagram, it would seem reasonable to expect that the distance between two sets of chromaticity coordinates would be correlated to how different the two colours represented by the chromaticity coordinates appear. While this is approximately true, the correlation is very low. This is because the CIE 1931 chromaticity diagram is perceptually non-uniform. Green colours cover a large area, while red colours are compressed into the bottom right corner. This perceptual nonuniformity makes any attempt to quantify large colour differences using the CIE 1931 chromaticity diagram futile. In an attempt to improve this situation, the CIE first introduced the CIE 1960 uniform chromaticity scale (UCS) diagram and then, in 1976, recommended the use of the CIE 1976 UCS diagram. Both diagrams are simply linear transformations of the CIE 1931 chromaticity diagram. The axes for the CIE 1976 UCS diagram are

$$u' = \frac{4x}{-2x + 12y + 3} \qquad v' = \frac{9y}{-2x + 12y + 3}$$

where x and y are the CIE 1931 chromaticity coordinates. Figure 1.6 shows the CIE 1976 UCS diagram.

While the 1976 UCS diagram is more perceptually uniform than the CIE 1931 chromaticity diagram, it is of limited value for determining colour differences. This is because it is 2D, considering only the hue and saturation of the colour. To completely describe a colour, a third dimension is needed, that of brightness for a self-luminous object and lightness for a reflecting object (Wyszecki, 1981). In 1964, the CIE introduced the U^*, V^*, W^* 3D colour space for use with surface colours, where

$$U^* = 13\ W^*(u - u_n)$$

$$V^* = 13\ W^*(v - v_n)$$

$$W^* = 13\ Y^{0.33} - 17 \quad \text{(where } Y \text{ has a range from 1 to 100)}$$

W^* is called a lightness index and approximates the Munsell value of a surface colour (see Section 1.6.2). The coordinates u, v refer to the chromaticity coordinates of the surface colour in the CIE 1960 UCS diagram, while the chromaticity coordinates u_n, v_n refer to a spectrally neutral colour lit by the source that is placed at the origin of the U^*, V^* system. This U^*, V^*, W^* system is of little use now; about the only purpose for which it is routinely used is the calculation of the CIE colour rendering indices (CRIs) (see Section 1.6.3.2).

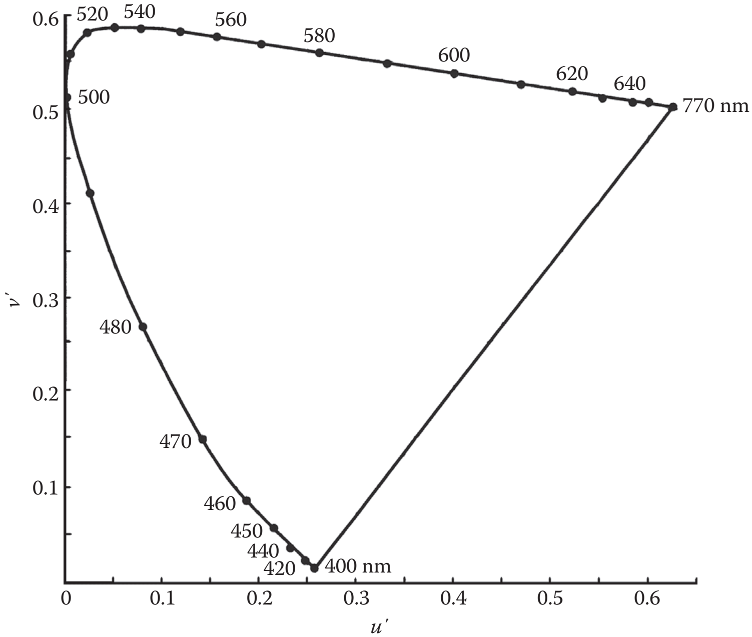

FIGURE 1.6 The CIE 1976 UCS diagram. (From Illuminating Engineering Society of North America (IESNA), *The Lighting Handbook*, 9th edn., IESNA, New York, 2000a.)

The U^*, V^*, W^* colour space is little used now because it has been superseded by two other colour spaces introduced by the CIE in 1976 (Robertson, 1977; CIE, 2004a). These two colour spaces are known by the initialisms CIELUV and CIELAB. They are both constructed to follow the structure of the human colour vision system (see Section 2.2.7). One dimension relates to the red-green colour channel, another relates to the blue-yellow colour channel and the third relates to the light–dark luminance channel.

The three coordinates of the CIELUV colour space are given by the expressions

$$L^* = \left[116\left(\frac{Y}{Y_n}\right)^{0.33} - 16\right] \quad \text{for } \frac{Y}{Y_n} > 0.008856$$

$$L^* = 903.29\left(\frac{Y}{Y_n}\right) \quad \text{for } \frac{Y}{Y_n} \le 0.008856$$

$$u^* = 13L^*(u' - u'_n)$$

$$v^* = 13L^*(v' - v'_n)$$

where

u' and v' are the chromaticity coordinates from the CIE 1976 UCS diagram

u'_n, v'_n and Y_n are values for a nominally achromatic colour, usually the surface with 100% reflectance ($Y_n = 100$) lit by the light source

The three coordinates of the CIELAB colour space are given by the expressions

$$L^* = 116 f\left(\frac{Y}{Y_n}\right) - 16$$

$$a^* = 500\left[f\left(\frac{X}{X_n}\right) - f\left(\frac{Y}{Y_n}\right)\right]$$

$$b^* = 200\left[f\left(\frac{Y}{Y_n}\right) - f\left(\frac{Z}{Z_n}\right)\right]$$

where
$f(q) = q^{0.33}$ for $q > 0.008856$
$f(q) = 7.787q + 0.1379$ for $q \leq 0.008856$
$q = X/X_n$ or Y/Y_n or Z/Z_n

Again, X_n, Y_n and Z_n are, respectively, the values of X, Y and Z for a nominally achromatic surface, usually that of the light source with $Y_n = 100$.

Each of these colour spaces has a colour difference formula associated with them. For the CIELUV colour space, the colour difference is given by

$$\Delta E^*_{uv} = [(\Delta L^*)^2 + (\Delta u^*)^2 + (\Delta v^*)^2]^{0.5}$$

For the CIELAB colour space, the colour difference is given by

$$\Delta E^*_{ab} = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{0.5}$$

These two colour spaces are now widely used to set colour tolerances for manufacture in many industries. As an indication of the perceptual uniformity of the CIELUV and CIELAB systems, Figure 1.7 shows loci of constant Munsell hue and chroma for a value of 5 (see Section 1.6.2), plotted on u^*, v^* and a^*, b^* planes through the CIELUV and CIELAB colour spaces (Anon, 1977). If the CIELUV and CIELAB colour spaces were perceptually uniform, these loci should form equally spaced concentric circles for saturation and equally spaced radial lines for hue. As can be seen in Figure 1.7, neither CIELUV nor CIELAB is perfectly perceptually uniform, but they both are a lot better than the alternative U^*, V^*, W^* colour difference system or the more basic 2D CIE UCS diagrams. Further, both CIELUV and CIELAB can be used as the basis for developing models of colour appearance (Hunt, 1982, 1987, 1991).

1.6.2 Colour Order Systems

While the CIE colorimetric system is valuable for quantifying colours, it does lack a physical presence. This need is met by a variety of colour ordering systems. A colour ordering system is a physical, 3D representation of colour space. In a

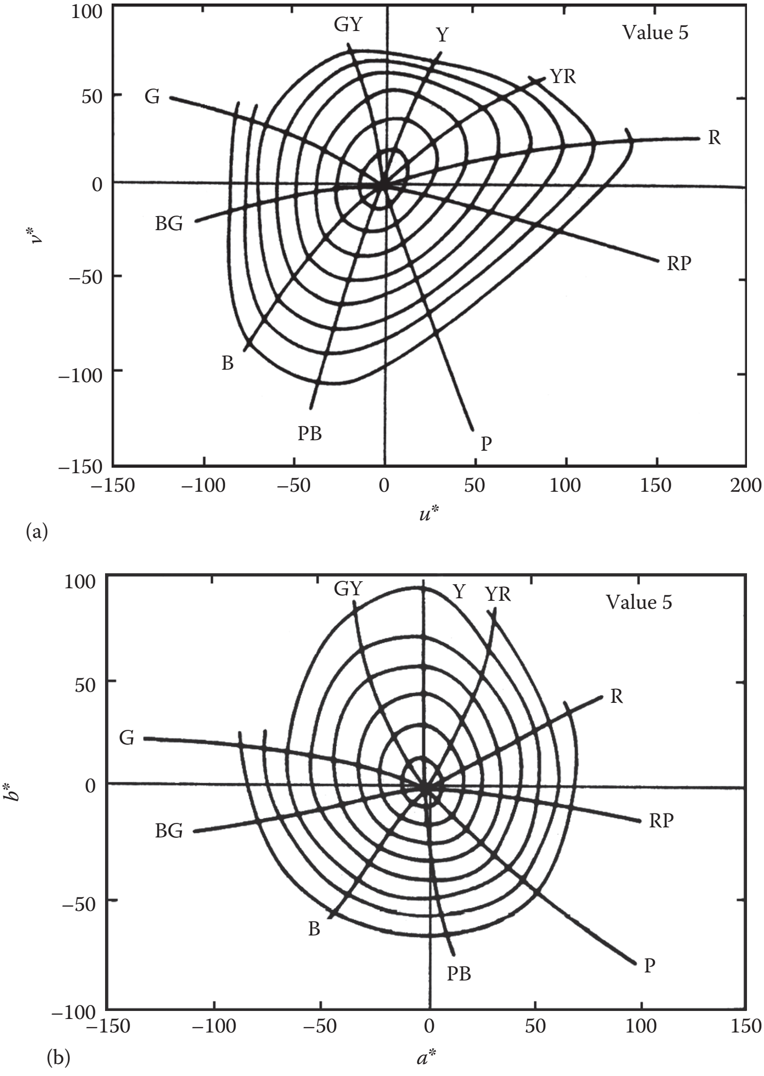

FIGURE 1.7 Loci of constant Munsell hue and chroma for a value of 5, plotted on planes through the (a) CIELUV and (b) CIELAB colour spaces. (From Illuminating Engineering Society of North America (IESNA), *The Lighting Handbook*, 9th edn., IESNA, New York, 2000a.)

sense, it is an atlas of colours, and like an atlas, the separation between adjacent colours is intended to be uniform in all directions. There are several different colour ordering systems used in different parts of the world (Billmeyer, 1987). One of the most widely used is the Munsell system. Figure 1.8 shows the organization of the Munsell system. The azimuthal hue dimension consists of 100 steps arranged around a circle, with five principal hues (red, yellow, green, blue and purple) and five intermediate hues (yellow-red, green-yellow, blue-green,

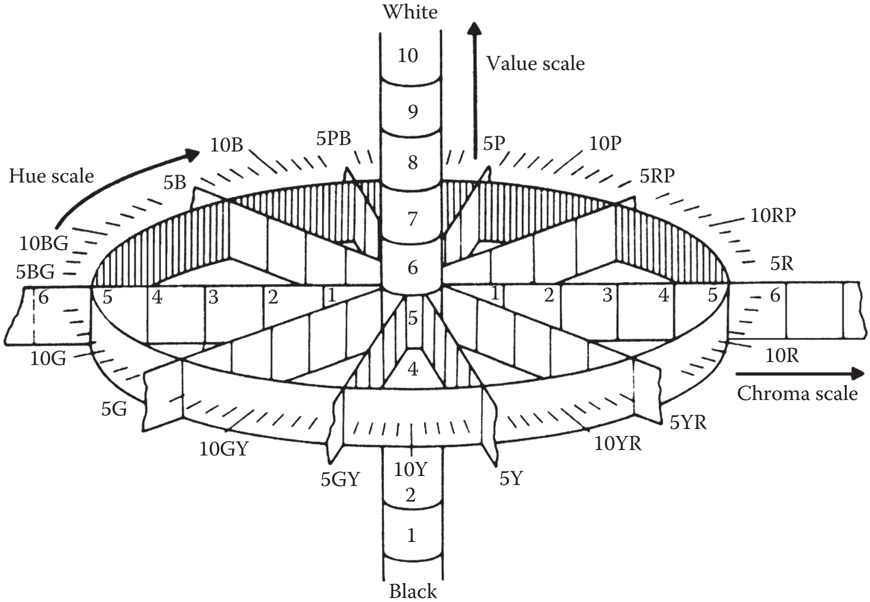

FIGURE 1.8 The organization of the Munsell colour order system. The hue letters are B, blue; PB, purple/blue; P, purple; RP, red/purple; R, red; YR, yellow/red; Y, yellow; GY, green/yellow; G, green; BG, blue/green.

purple-blue and red-purple). The vertical value scale contains 10 steps from black to white. The horizontal chroma scale contains up to 20 steps from neutral to highly saturated. Each of the three scales is designed to provide equal steps of perception for an observer with normal colour vision looking at the samples lit by daylight, with a grey or white surround. The position of any colour in the Munsell system is identified by an alphanumeric reference made up of three terms, hue, value and chroma, for example, a strong red is given the alphanumeric 7.5R/4/12. Achromatic surfaces, that is, colours that lie along the vertical value axis and hence that have no hue or chroma are coded as Neutral 1, Neutral 2, etc., depending on their reflectance. To a first approximation, the percentage reflectance of a surface is given by the product of V and $(V - 1)$ of the surface, where V is the Munsell value of the surface.

The utility of a colour ordering system is that it makes colours manifest and hence makes it easy to communicate about colour in a more precise way than words permit. For example, rather than someone in New York telling someone in London that the required colour is lightish, yellowish green, it is much better to say that the colour required is Munsell reference 5YG/8/2 because then, provided both parties have access to a Munsell system publication, they can physically see what the required colour is. While communicating through the Munsell system, or any other colour ordering system, is more precise than words, it is not as precise as using the numbers generated by the CIE colour spaces following measurement (Hunt and Pointer, 2011). However, sometimes precision has to give way to convenience. Building materials, such as paints, plastic and ceramics, are commonly classified in terms of a colour ordering system.

The existence of several different colour ordering systems used in different parts of the world, as well as the quantitative CIE colorimetry system, would seem to be a recipe for confusion. Fortunately, this is usually avoided by the fact that conversions are available between many of the colour ordering systems and the CIE colorimetry system. For example, the German DIN system provides both Munsell and CIE equivalents of its components (Richter and Witt, 1986). The name categories of the Inter-Society Colour Council–National Bureau of Standards method (Kelly and Judd, 1965) are given in terms of the Munsell system (National Bureau of Standards, 1976). Conversions between the CIE colorimetry system and the Munsell system are given by the American Society for Testing and Materials (ASTM, 2012).

1.6.3 Application Metrics

While the CIE colorimetry system is the most complete and most widely accepted means of quantifying colour, it is undeniably complex. Therefore, the lighting industry has used the CIE colorimetry system to derive two single-number metrics to characterize the colour properties of light sources: correlated colour temperature (CCT) and the CIE general CRI. These two metrics are given in most lamp manufacturers' catalogues. CCT is a metric for the colour appearance of the light emitted by a light source. The CIE general CRI is a metric of the effect a light source has on the appearance of surface colours relative to the effect of a reference light source.

1.6.3.1 Correlated Colour Temperature

In principle, the colour of the light emitted by a light source can be characterized by its chromaticity coordinates. In practice, this is rarely done. Rather, the CCT is used. The basis of this measure is the fact that the spectral emission of a black body is defined by Planck's radiation law and hence is a function of its temperature only. Figure 1.9 shows a section of the CIE 1931 chromaticity diagram with the Planckian locus shown. The locus is the curved line joining the chromaticity coordinates of black bodies at different temperatures. The lines running across the Planckian locus are iso-temperature lines. When the chromaticity coordinates of a light source lie directly on the Planckian locus, the colour appearance of that light source is expressed by the colour temperature, that is, the temperature of the black body that has the same chromaticity coordinates. For light sources that have chromaticity coordinates close to the Planckian locus but not on it, their colour appearance is quantified as the CCT, that is, the temperature of the iso-temperature line that is closest to the actual chromaticity coordinates of the light source. The temperatures are usually given in degrees Kelvin (K). An alternative metric, namely, reciprocal colour temperature, is sometimes used, this being measured as 1,000,000 divided by the CCT measured in Kelvin and expressed as reciprocal megaKelvin (MK^{-1}).

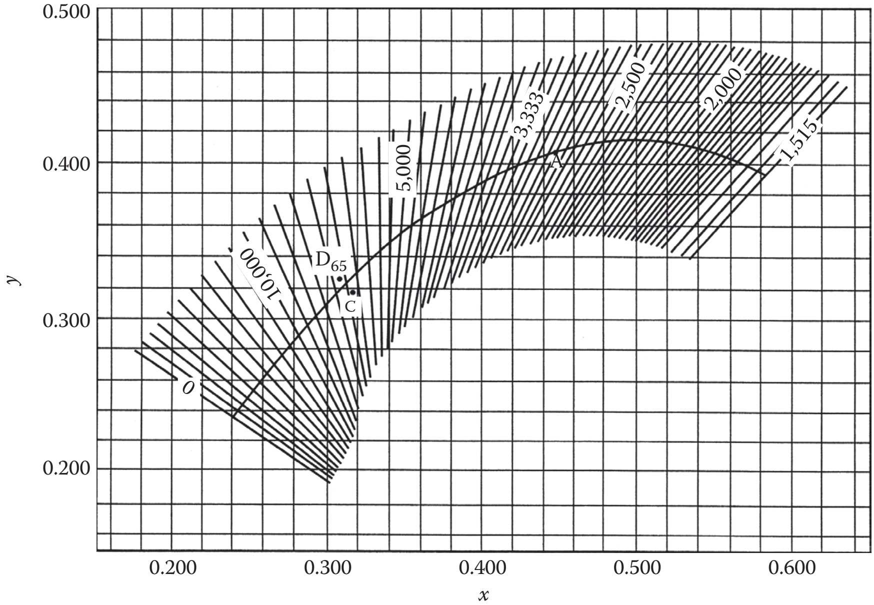

FIGURE 1.9 The Planckian locus and lines of constant CCT plotted on the CIE 1931 (x, y) chromaticity diagram. Also shown are the chromaticity coordinates of CIE Standard Illuminants, A, C and D65. (From Illuminating Engineering Society of North America (IESNA), *The Lighting Handbook*, 9th edn., IESNA, New York, 2000a.)

The advantage of this metric is that a difference of 1 MK^{-1} indicates approximately the same colour difference at any colour temperature above 1800 K.

CCT is a very convenient and easily understandable metric of light source colour appearance, applicable to nominally white light sources. As a rough guide, such light sources have CCTs ranging from 2,700 to 17,000 K. A 2,700 K light source, such as an incandescent lamp, will have a yellowish colour appearance and be described as warm, while a 17,000 K light source, such as some types of fluorescent lamp, will have a bluish appearance and be described as cold. The CCTs of the most commonly used light sources lie in the range 2700–5000 K.

It is worth noting that two light sources with the same CCT can have different colour appearances. This is because the two light sources can lie at different points along the specific iso-temperature line and hence have different chromaticity coordinates.

It is also important to appreciate that light sources that have chromaticity coordinates distant from the Planckian locus should not be given a CCT. Such lamps will appear greenish when the chromaticity coordinates lie above the Planckian locus or purplish if they lie below it. There is a metric that sets limits as to how far away from the Planckian locus the chromaticity coordinates of a solid-state light source can be if it is to be considered a source of white light. This metric, called Duv, is the distance between the chromaticity coordinates of the light source and the nearest point on the Planckian locus, measured on the CIE 1976 UCS diagram. The maximum allowed Duv values are ±0.006, positive values being for chromaticity coordinates above, and negative for below, the Planckian locus (ANSI, 2008). Both CCT and Duv are necessary to define the colour appearance of a light source.

While setting a limit to how far away from the Planckian locus the chromaticity coordinates of a light source can be while still claiming to produce white light is a definite step forward, there may still be some work to do in this area. This is because there is some evidence that below about 4000 K, the chromaticity coordinates considered to represent white light depart from the Planckian locus (Rea and Freyssinier, 2013). It remains to be seen if the Duv metric will be modified to follow this departure.

1.6.3.2 CIE Colour Rendering Index

As for the effect a given light source will have on the appearance of surface colours, in principle, this can be given by calculating the chromaticity coordinates of each colour in one of the CIE colour spaces. Differences between different surface colours can then be estimated by calculating their separation in colour space. This is reasonable if a specific set of surface colours is of interest, but for most lighting applications, where many different but unspecified surface colours are used, more general advice is desirable. This is where the CIE CRI comes in. The CIE CRI measures how well a given light source renders a set of standard test colours relative to their rendering under a reference light source of the same CCT as the light source of interest (CIE, 1995). The reference light source used is an incandescent light source for light sources with a CCT below 5000 K and some form of daylight for light sources with CCT above 5000 K. The actual calculation involves obtaining the positions of a surface colour in the CIE 1964 U^*, V^*, W^* colour space under the reference light source and under the light source of interest and expressing the difference between the two positions on a scale that gives perfect agreement between the two positions a value of 100. The CIE has 14 standard test colours. The first eight form a set of pastel colours arranged around the hue circle. Test colours 9–14 represent colours of special significance, such as skin tones and vegetation. The result of the calculation for any single colour is called the CIE special CRI, for that colour. The average of the special CRIs for the first eight test colours is called the CIE general CRI. It is this latter index that is usually presented in light source manufacturers' catalogues.

The CIE general CRI has its limitations (Guo and Houser, 2004). First, it should be appreciated that just because two light sources have the same general CRI, it does not mean that they render colours the same way. The general CRI is an average, and there are many combinations of special CRI values that give the same average. Second, different light sources are being compared with different reference light sources. This makes the meaning of comparisons between different light sources uncertain, yet comparing light sources is what the general CRI is most widely used to do. Third, chromatic adaptation is dealt with by using the Von Kries transform which has been found to be inadequate (CIE, 2004b). Fourth, the range of test colours is limited. None are saturated. Fifth, there has to be some doubt about whether the reference light sources, either incandescent or daylight, represent perfect colour rendering. These limitations should be borne in mind when evaluating the CIE general CRIs for different light sources.

1.6.3.3 Colour Vector Maps

The great attraction of the CIE general CRI is that it reduces the complexity of the rendering of colours to a single number. But this reduction leads to a considerable loss of information. An alternative but similar approach to quantifying the colour properties of light sources that preserve the complexity of colour rendering has been developed by Philips Lighting BV. Figure 1.10 shows a plot of the difference in position in colour space for 215 test colours (Opstelten, 1983) when lit by the light source of interest and a reference light source of the same CCT, plotted on the *a**, *b** plane of the CIELAB colour space (van Kemenade and van der Burgt, 1988). The origin of each arrow on the map is the chromaticity of the colour under the reference light source, and the head of the arrow is the chromaticity of the colour when lit by the light source of interest. Obviously, the shorter the arrows, the closer the light source of interest renders colours relative to their rendering under the reference light source. Further, the direction of the arrow gives the direction of any change in colour rendering. Arrows that point towards the origin of the figure indicate a reduction in chroma under the light source of interest, while arrows that point across radial lines from the origin indicate a shift in hue. A common feature of Figure 1.10 is that greater colour shifts occur in some hue/chroma areas and smaller shifts occur in others. Clearly, such a method of displaying the colour rendering properties of light sources gives much more information than the single number of the CIE general CRI, but understanding the diagram requires some thought which has limited its popularity.

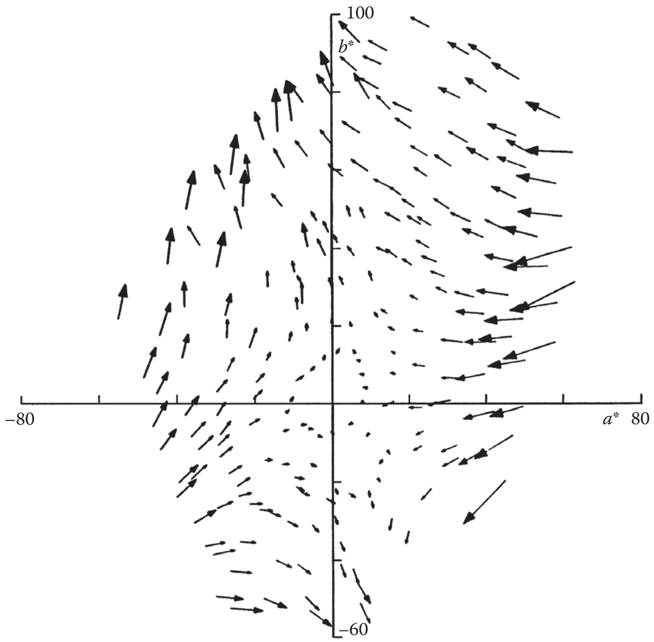

FIGURE 1.10 Colour mismatch vectors for 215 object colours projected onto the *a** *b** plane of the CIELAB colour space for a metal halide (MH) lamp. (After van Kemenade, J.T.C. and van der Burgt, P.J.M., Light sources and colour rendering: Additional information for the Ra Index, *Proceedings of the CIBSE National Lighting Conference*, CIBSE, London, U.K., 1988.)

1.6.4 Colour Quality

While CCT and the CIE general CRI remain the most widely used application metrics for describing light source colour properties, the arrival on the market of solid-state light sources producing white light from a combination of three or more narrowband LEDs has caused some consternation. The problem is that such solid-state light sources produce values of the general CRI that do not match how people evaluate their colour rendering (CIE, 2007). The result has been the same as occurred when fluorescent lamps first became widespread, a renewed interest in approaches to quantifying light source colour properties. The outcome of this interest has been an outburst of new methods. These can be divided into four types.

1.6.4.1 Refined Colour Rendering

The first type follows the same approach as that used in the CRI in that the performance of a test source is compared with that of a reference source. An example of this approach is the colour quality scale (CQS) method (Davis and Ohno, 2010). This uses the same reference light sources as the CIE CRI. Where it differs is in having 15 saturated test colours, using the CIELAB colour space and a better transform to allow for colour adaptation, ignoring any difference in chromaticities where the test source enhances the saturation of the colour relative to the reference light source and taking the root mean square of the remaining differences between the chromaticity coordinates of each test colour under the test and the reference light sources. The result is a single number scaled between 0 and 100. The CQS produces general CQS indices for fluorescent lamps that are very similar to those produced by the CRI method but produces rather different values for white, narrowband LED light sources.

In addition to the general CQS value, each test colour has its own special CQS value, and there are two other general CQS indices (Davis and Ohno, 2010). These are the colour fidelity index and the colour preference index. The colour fidelity index treats all differences between the chromaticity coordinates under the test and reference sources equally, regardless of whether they increase or decrease saturation. Thus, the colour fidelity index is a true measure of how accurately the test light source matches the performance of the reference light source. The colour preference index gives additional weight to the differences where the test light source enhances the saturation of colours. This is because it has been shown that people generally prefer colours to be more saturated than they usually are (Judd, 1967; Thornton, 1972).

1.6.4.2 Colour Gamut

The second approach to characterizing light source colour properties does not use a reference light source. It is called the colour gamut approach. The colour gamut is obtained by calculating the chromaticity coordinates of a set of test colours under the light source of interest and plotting them on a plane in colour space. When the plotted positions are joined together, the colour gamut is formed. Figure 1.11 shows the colour gamuts for the first eight CIE test colours illuminated by a number of different light sources plotted on the CIE 1976 UCS diagram. A great deal can be learnt from

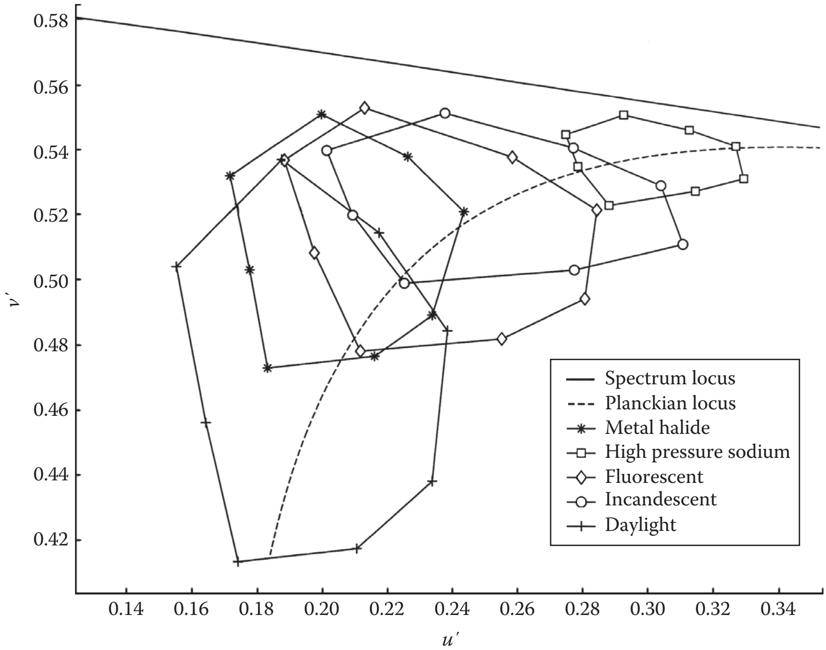

FIGURE 1.11 The colour gamuts for high pressure sodium (HPS), incandescent, fluorescent and metal halide light sources, and for the CIE Standard Illuminant D65, simulating daylight, all plotted on the CIE 1976 UCS diagram. The dotted curve is the Planckian locus.

the colour gamut. From a consideration of its shape and the spacing between the positions of the individual test colours, the extent to which the different parts of the hue circle can be discriminated is apparent. From its location on the CIE 1976 UCS diagram, the appearance of colours can be appreciated to some degree. By plotting different light sources on the same diagram, it is easy to make comparisons between light sources. Further, by including the colour gamut of an ideal light source, such as daylight, it is possible to establish how close the light source of interest comes to the ideal.

The colour gamut as shown in Figure 1.11 requires the viewer to appreciate the implications of the shape and position of the gamut. This requirement for thought has led to suggestions that the colour gamut be reduced to a single number by calculating the area enclosed by the gamut as a metric of colour rendering. Gamut area suffers from the defects of any single-number index, in that light sources with the same gamut area can render colours differently. It is even possible to express the gamut area relative to that of an ideal light source. The gamut area scale suggested by Davis and Ohno (2010) relates the gamut area created by calculating the positions of the 15 test colours used in the CQS (see Section 1.6.4.1) on the a', b' plane of the CIELAB colour space to the area enclosed by the same test colours illuminated by the CIE D65 illuminant representing daylight. Rea and Freyssinier (2010) introduce a gamut area index based on the positions of the first eight CRI test colours plotted on the 1976 UCS diagram when illuminated by the light source of interest and by an equal energy spectrum as the ideal. The gamut area under the equal energy spectrum is given a value of 100. The gamut area under the light source of interest is then scaled accordingly. It is worth noting that this process means the gamut area index can be greater than 100.

A somewhat different colour gamut approach is to calculate the volume in CIELUV colour space occupied by all the colours that a light source can produce. This number is called the colour rendering capacity (Xu, 1993). This metric says nothing about how accurately colours are rendered but does indicate the potential for producing saturated colours.

1.6.4.3 Spectrum-Based Colour Metrics

Another approach to characterizing light source colour properties is based on deviations from an ideal spectrum. The difficulty with this approach is deciding on what is the ideal spectrum. Rea et al. (2005a) adopted the equal energy spectrum as the ideal on the basis that this is what people should mean when they talk about full-spectrum lighting. The sum of squares of the deviations of the actual spectrum of the light source from the equal energy spectrum was calculated; the smaller the sum, the better. The number produced was called the full-spectrum index.

1.6.4.4 Colour Appearance Models

Another approach to exploring the colour properties of light sources involves the use of the colour appearance models. Pointer (1986) used the Hunt (1982) model to generate 15 different measures relating to hue, chroma and lightness. Szabo et al. (2009) used the CIECAM02 model (CIE, 2004c) to generate metrics relating to the harmony of colour pairs and triads. Both these approaches assume a reference light source and can be used to develop single-number metrics. However, it seems perverse to use a very sophisticated model of colour appearance to generate a comprehensive picture of how a light source will influence surface colours only to throw almost all of that information away by reducing the description to a single number.

1.6.4.5 Scotopic/Photopic Ratio

One other measure of light source colour characteristics that has been gaining interest in recent years is the scotopic/photopic ratio (Berman, 1992). This is calculated by taking the relative spectral power distribution, in radiometric units, of the light source and weighting it by the CIE standard scotopic and photopic observers and expressing the resulting scotopic lumens and photopic lumens as a ratio. The value of scotopic/photopic ratios is that they express the relative effectiveness of different light sources in stimulating the rod and cone photoreceptors in the human visual system. A light source with a higher scotopic/photopic ratio will stimulate the rods more than a light source with a lower scotopic/photopic ratio when both produce the same photopic luminous flux. This information is useful when considering light sources for applications where the visual system is operating in the mesopic state.

1.6.4.6 Conclusion

By now, it should be apparent that quantifying colour is complicated, and using simple metrics requires some recognition that information has been lost. Guo and

Houser (2004) suggested that at least two single-number metrics are required to give a meaningful picture of any light source, one relative measure in which a reference source is used, for example, CRI or CQS, and one absolute measure without a reference source, for example, gamut area. This view is supported by the results of Rea and Freyssinier (2010), Smet et al. (2011) and Dangol et al. (2013). Others have pointed out the possibility of developing metrics based on colour differences (Sandor and Schanda, 2006), colour harmony (Szabo et al., 2009) or memory colours, that is, the colours of objects where colour carries a meaning such as fruit (Smet et al., 2010). Yet others have developed detailed models of colour appearance (Fairchild, 2005). Which of these approaches should be used will vary with circumstances. The colour appearance models can only be used where the décor of the space is known and are only appropriate where detailed information on colour appearance is required. However, in this situation, there is a lot to be said for using a mock-up to make visual assessments rather than calculation. In practice, the lighting of a space is often designed before the final choice of décor is made. In this situation, the best approach would seem to be to use a number of measures. Rea et al. (2004b) illustrated such an approach using three different colour metrics: CRI, gamut area index and full-spectrum index, together with luminous efficacy (see Section 1.7.4). Even this may be too complex for some, so Rea (2013) suggests establishing what are called Class A colour light sources. These are light sources with a CRI greater than or equal to 80, a gamut area index between 80 and 100 and chromaticity coordinates that follow the white line of minimum tint identified by Rea and Freyssinier (2013). Other people will prefer other combinations of metrics, and different weights will be given to different colour metrics in different situations but one thing is certain – the world of lighting has to move on from a reliance on CCT and CRI as the only metrics that need to be considered when assessing the colour properties of a light source.

1.7 SOURCES OF LIGHT

Illumination is produced naturally, by the sun, and artificially, by oil and gas flames and electric light sources. The development and growth in use of artificial sources of light over the last century has fundamentally changed the pattern of life for millions of people on Earth.

1.7.1 Natural Light

Natural light is light received on Earth from the sun, either directly or after reflection from the moon. The prime characteristic of natural light is its variability. Natural light varies in magnitude, spectral content and distribution with different meteorological conditions, at different times of day and year and at different latitudes. Moonlight is of little interest as a source of illumination, but daylight is used, and strongly desired, for the lighting of buildings. Daylight can be divided into two components: sunlight and skylight. Sunlight is light received at the Earth's surface directly from the sun. Sunlight produces strong, sharp-edged shadows. Skylight is light from the sun received at the Earth's surface after scattering in the atmosphere. It is this scattered light that gives the sky its blue appearance, as compared to the blackness of space.

Skylight produces only weak, diffuse shadows. The balance between sunlight and skylight is determined by the nature of the atmosphere and the distance that the light passes through it. The greater the amount of water vapour and the longer the distance, the higher is the proportion of skylight.

Daylight varies from time to time and from site to site in amount, spectrum and distribution. The illuminances on the Earth's surface produced by daylight can cover a large range, from 100,000 lx on a sunny summer's day to 1,000 lx on a heavily overcast day in winter. Figure 1.12 shows a spectral power distribution of daylight. It is clear that daylight contains significant amounts of ultraviolet (UV) and infrared (IR) radiation and that, over the visible wavelengths, daylight is a continuous spectrum. The CCT of daylight can range from 4,000 K for an overcast day to 40,000 K for a clear blue sky. For calculating the appearance of objects under natural light, the use of one of three different spectral distributions corresponding to CCTs of 5500, 6500 and 7500 K is recommended (Wyszecki and Stiles, 1982). As for distribution, this can range from a completely overcast sky to a completely clear sky. A completely overcast sky has a luminance distribution that is symmetrical about a vertical axis, and the luminance at the zenith is about three times that at the horizon. When the sky is clear or partly cloudy, the luminance distribution is not symmetrical about the azimuth, the highest luminances occurring around the sun. The CIE has identified 15 different sky luminance distributions covering the range from completely overcast to completely clear (CIE, 2004d).

The main use of such information is to estimate the amount of daylight admitted to a building through windows and the consequences for the use of electric lighting and air-conditioning over the year. A simple worst-case approach is still sometimes used, namely, to assume a completely overcast sky producing a horizontal illuminance of 5000 lx on the ground. This, combined with daylight factor, is enough to estimate the amount of daylight arriving at a point in a space. Daylight factor is the ratio of the daylight illuminance delivered directly and indirectly to a point in a space to the horizontal illuminance outside and unobstructed. Of course, this only

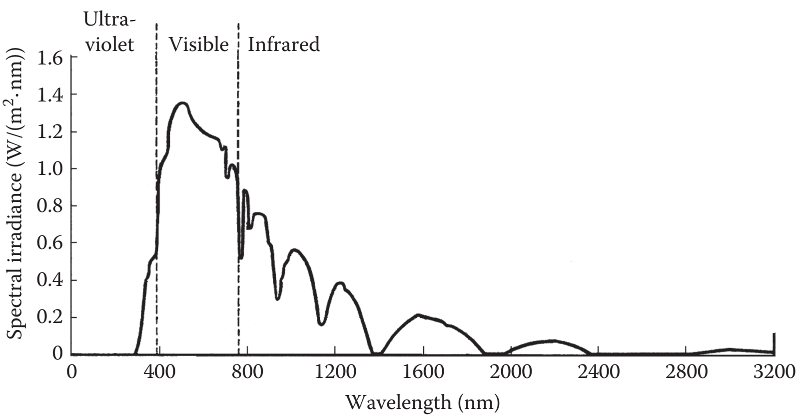

FIGURE 1.12 The spectral irradiance of daylight over the UV, visible and IR regions of the electromagnetic spectrum. (From Illuminating Engineering Society of North America (IESNA), *The Lighting Handbook*, 9th edn., IESNA, New York, 2000a.)

gives an estimate of the daylight contribution under one sky condition and at one illuminance, yet over a year, a building may experience many different sky conditions and hence many different illuminances. Fortunately, annual climate data are now available for many locations in the world. This makes it possible to use climate-based daylight modelling to assess the impact of daylight availability over a year (Mardaljevic et al., 2009). Associated with climate-based daylight modelling are two other daylight metrics. One is useful daylight illuminance (Nabil and Mardaljevic, 2005). This metric is based on the illuminance provided by daylighting in a space. Illuminances below 100 lx are considered to be of little use as the artificial lighting will be on all the time. Illuminances above 2000 lx are also not useful because they are often associated with glare and an increased use of air-conditioning. Useful daylight illuminance is defined as the percentage of annual operating hours of a space for which the illuminance provided by daylight is within the range 100–2000 lx. The other metric is daylight autonomy (Reinhart et al., 2006). This is defined as the percentage of annual operating hours for a space in which a given daylight level is exceeded. Such measures can be used to estimate the cost benefits of using a lighting control system linked to daylight.

While such measures are undeniably important for estimating the energy consumption of a building, they tell us little about the human response. For the human response, much more important is where and when sunlight occurs. This is important because sunlight in the wrong place at the wrong time can cause discomfort and be a potent cause of windows being obstructed by blinds. For a given site and building, where and when sunlight will occur can be reliably predicted using sun path diagrams (Hopkinson et al., 1966). Advice on these and many other aspects of daylight design can be found in Tregenza and Wilson (2011) and Kittler et al. (2012). Regardless of how it is predicted and quantified, daylight is highly regarded by people, at least in climates where daylight is limited for part of the year. It has a marked effect on the design and control of buildings in all climates.

1.7.2 Artificial Light: Flame Sources

The first form of artificial lighting used by humans was firelight, created by the combustion of wood. Developments in basic technology have led to the creation of the oil lamp, the candle and, ultimately, the gas lamp, all of which depend on combustion of a fuel. Oil lamps, candles and gas lamps are sometimes used today, either through necessity or for the atmosphere they evoke. However, they are rarely used for functional lighting where an electricity supply is available. This is for three reasons. The first is the fire hazard posed by open flames in buildings. The second is the level of air pollution produced by combustion of fuel in confined spaces. The third, and the most important, is the low luminous efficacy of these flame sources. Luminous efficacy is the ratio of the amount of light emitted by the light source to the power supplied to it and is measured in lumens/watt. Typical luminous efficacy values for candles, oil lamps and gas flames are 0.1, 0.3 and 1 lm/W, respectively. These values are two orders of magnitude lower than the ubiquitous fluorescent lamp widely used for functional lighting in commercial buildings and one order of magnitude less than the incandescent lamp still commonly used in homes.

1.7.3 Artificial Light Sources: Electric/General Illumination

The lighting industry makes several thousand different types of electric lamps. Those used for providing general illumination can be divided into three classes: incandescent lamps, discharge lamps and solid-state lamps. Incandescent lamps produce light by heating a tungsten filament to incandescence. Discharge lamps produce light by an electric discharge in a gas. Solid-state lamps produce light by passing a current through a semiconductor junction. Incandescent lamps operate directly from the electricity supply. Discharge lamps require control gear between the lamp and the electricity supply because different electrical conditions are required to initiate the discharge and to sustain it. Solid-state lamps require control gear to convert the AC mains supply to DC and to limit the current through the junction.

1.7.3.1 Incandescent Lamp

The most common form of incandescent lamp is known to many as the household bulb. This produces light by heating a thin tungsten filament to incandescence in an inert gas atmosphere. The spectral emission of the incandescent lamp is a continuum over the visible spectrum (Figure 1.13), although the exact spectrum is determined by the temperature of the filament. This is easily seen when an incandescent lamp is dimmed. Reducing the voltage reduces the current through the filament and hence the temperature of the filament. The result is that the colour appearance of the light emitted by the lamp becomes more yellow and then red until, at very low voltages, no light can be seen at all, although the lamp may still be emitting IR radiation. The design of an incandescent lamp is a matter of balancing luminous efficacy against life. A high light output and hence a higher luminous efficacy can be achieved by heating the filament to just below its melting point but then the life is short. When a long lamp life is desirable, as in traffic signals, the filament is heated to a lower than usual temperature. For incandescent lamps used in households around the world, the luminous efficacy is around 12 lm/W and the life is about 1000 h. The incandescent lamp has been commercially available since the 1880s and is probably still the most widely used lamp in the world, but not for much longer. In a number of major countries, the basic household bulb is being forced off the market by political diktat in the name of reducing carbon emissions (see Section 16.3). This is despite the fact that it is small, cheap, simple to operate, has reasonable colour properties and is easy to dim.

1.7.3.2 Tungsten Halogen Lamp

The tungsten halogen lamp is essentially an incandescent lamp with a halogen in the gas filling. The inclusion of the halogen allows the filament to be run at a higher temperature because, although the tungsten is evaporated off the filament faster at the higher temperature, the halogen chemically reacts with the evaporated tungsten to form a tungsten halogen compound which diffuses back to the filament where the higher temperature causes it to separate into tungsten and halogen, depositing the tungsten back on the filament. This cycle ensures the light output is maintained at a higher level for longer than would be the case without the halogen. The higher filament temperature also implies a higher luminous efficacy,

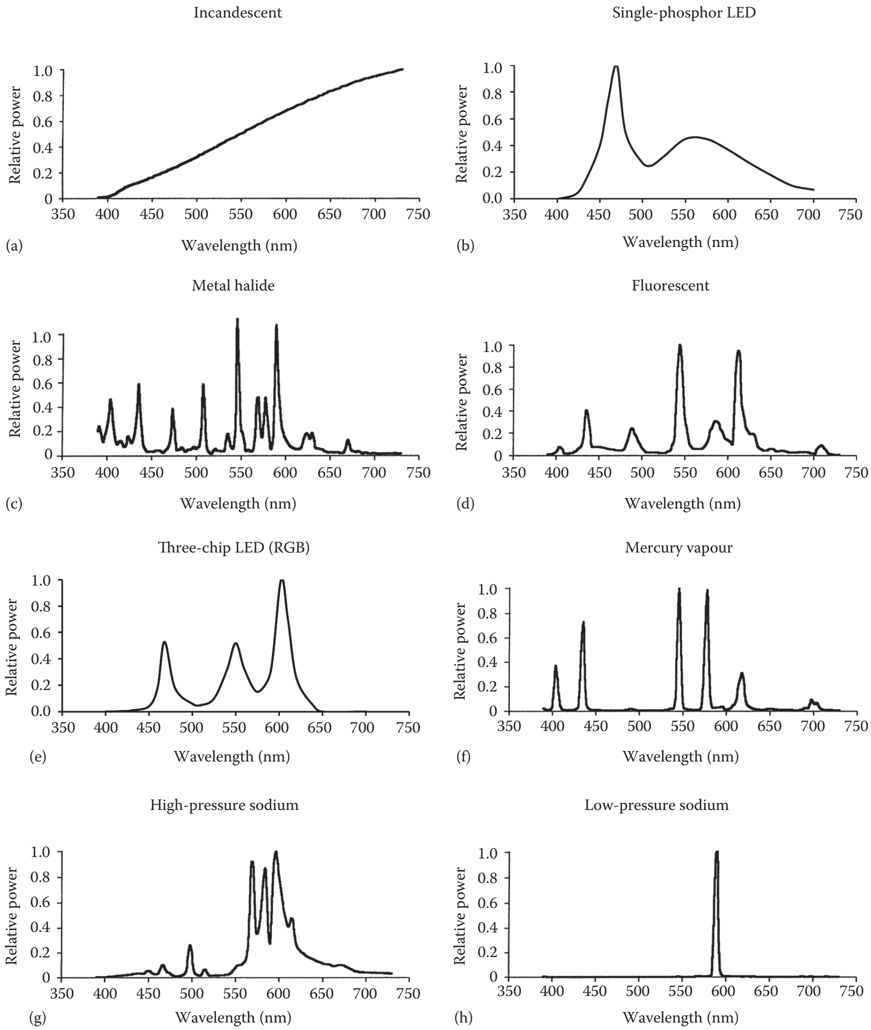

FIGURE 1.13 Relative spectral power distributions for different light sources. The light sources shown are (a) incandescent, (b) single-phosphor LED, (c) MH, (d) fluorescent, (e) three-chip LED, (f) mercury vapour, (g) HPS and (h) LPS. All the spectral power distributions are normalized to unity for the wavelength with the maximum output. These spectral power distributions are illustrative only. Different lamps of the same type can vary in their spectral power distribution, particularly fluorescent and MH.

around 20 lm/W. The spectral emission of the tungsten halogen lamp is a continuum across the visible spectrum, as would be expected given its fundamental incandescent nature. The tungsten halogen lamp has been commercially available since the 1960s. Its small size, in combination with an appropriate reflector, has made it a favourite for accent lighting in retail applications but not for much longer. The tungsten halogen lamp is scheduled to go the same way as the incandescent lamp within a few years.

1.7.3.3 Fluorescent Lamp

The fluorescent lamp is a discharge lamp in that the physical means for producing light is the excitation of a gaseous discharge. The fluorescent lamp, in either its linear or compact form, consists of a glass tube containing a mercury atmosphere. Heating the electrodes produces a stream of electrons. These electrons are accelerated through the mercury gas by the potential difference between the electrodes. The accelerated electrons collide with the gas atoms producing two effects. The first is the ionization of the atom into electrons and a positively charged particle called an ion. This increases the electron concentration and hence maintains the discharge. The second possible outcome is that the atom absorbs most of the energy of the colliding electron and thereby raises the energy state of its own captive electrons to a higher level. These energy levels are discrete, and when the captive electrons shortly afterwards decay back to their resting level, energy is radiated at a wavelength determined by the energy level structure of the atom. For mercury at a low pressure, which is what fills a fluorescent lamp, most of the radiation emitted by the discharge is in the UV region of the electromagnetic spectrum. To produce radiation in the visible spectrum, the inner surface of the glass tube is coated with a phosphor. This absorbs the UV radiation from the discharge and emits radiation in the visible spectrum. This two-step process is evident in the spectral emission of the fluorescent lamp (see Figure 1.13), which usually consists of a series of strong emission lines, from the discharge, superimposed on a continuous emission spectrum, from the phosphor. By changing the phosphor mix, different spectral emissions can be created, so fluorescent lamps are available with a wide range of colour properties.

The fluorescent lamp is a discharge lamp and therefore needs to have a control system to alter the electrical conditions from those required to start the discharge to those required to maintain it. This control system, which is sometimes called a ballast, can be electromagnetic or electronic. Ballasts are available that make it possible to dim fluorescent lamps over a wide range with little change in colour properties. The fluorescent lamp has been commercially available since the late 1930s. Today, it is available in both tubular and compact forms and is widely used in commercial applications, mainly because of its high luminous efficacy (in the range 20–96 lm/W) and long life (up to 19,000 h).

1.7.3.4 Mercury Vapour Lamp

The mercury vapour lamp is similar to the fluorescent lamp in that it is a discharge lamp based on a mercury atmosphere in an arc tube. The difference is that the mercury vapour lamp is a high-pressure lamp. The result is that the spectral emission of the gas discharge is moved into the visible region, although it still consists of a series of intense spectral lines (see Figure 1.13). The mercury vapour lamp is also available with a phosphor coating on the inside of the envelope, the phosphor coating being used to improve the colour properties of the lamp. The mercury vapour lamp has been commercially available since the early 1930s and is now fading into disuse. It has a lower luminous efficacy than competing high-pressure discharge lamps and poor colour properties.

1.7.3.5 Metal Halide Lamp

The metal halide (MH) lamp is also a high-pressure gas discharge lamp based on a mercury discharge, but it is different from the mercury vapour lamp in that it has MHs, such as scandium and sodium iodides, in the arc tube. When the arc tube reaches an operating temperature, the MHs are vapourized. At the core of the discharge, the MHs separate into metals and halogen, the metals emitting radiation in the visible region. At the cooler edge of the arc tube, the metals and halogen recombine and then repeat the process. The result is a spectrum consisting of many discrete spectral lines (see Figure 1.13). As may be imagined, the chemistry of the MH lamp is very complex. The result is that early MH lamps gained a reputation for showing shifts in colour properties over life and even between different lamps from the same manufacturer when new. Developments in arc tube materials and design have gone a long way to alleviate this problem (van Lierop et al., 2000). The MH lamp was introduced to the market in the late 1960s and is now the lamp of choice where a high lumen output light source with high luminous efficacy and good colour properties is required, although this status is being challenged by solid state lighting.

1.7.3.6 Low-Pressure Sodium Lamp

The other broad class of discharge lamp is based around sodium. Electrically, the low-pressure sodium (LPS) lamp operates in the same manner as the fluorescent lamp, but in this case, a phosphor is unnecessary because the spectral emission from the sodium discharge is concentrated in two spectral lines, which are both close to 589 nm. Because this wavelength is near to the peak spectral sensitivity of the human visual system at 555 nm, the LPS lamp has the highest luminous efficacy of all the artificial light sources (up to 180 lm/W). Unfortunately, its colour properties are what might be expected from a monochromatic source, non-existent. For this reason, its use is restricted to applications where colour is of little consequence, such as road lighting away from inhabited areas, and then only in countries where luminous efficacy is valued above all else.

1.7.3.7 High-Pressure Sodium Lamp

Conceptually, the high-pressure sodium (HPS) lamp is the same as the LPS lamp, but the much higher pressure has an effect on the spectral emission. The increased pressure in the discharge leads to self-absorption of radiation within the discharge and interactions between the closely packed atoms. The combined effect of these phenomena is to reduce the power at 589 nm and to spread the spectral emission over a much wider range of wavelengths (see Figure 1.13). The result is a combination of high luminous efficacy and modest colour properties. Exactly what the balance is between luminous efficacy and colour properties depends on the pressure in the arc tube. Two levels of pressure are commercially produced. One produces light with an orange colour appearance but has a high luminous efficacy. The other produces light with a white colour appearance but with a lower luminous efficacy. The former is commonly used for street lighting and in industrial applications. The latter is sometimes used for display lighting. The HPS lamp in its high luminous efficacy form has been commercially available since the early 1960s. It soon replaced the mercury vapour lamp to become the most widely used light source for exterior lighting and for much industrial lighting, although both these positions are now being challenged by the MH lamp and solid-state lighting.

1.7.3.8 Electrodeless Lamps

All the discharge light sources discussed earlier create a discharge by applying a voltage across two electrodes placed in the arc tube. Two forms of electrodeless lamps are also available. One uses an electromagnetic field to create a plasma in a sealed enclosure. These are called induction lamps and are essentially a fluorescent lamp. The electromagnetic field excites the mercury in the enclosure that then emits radiation mainly in the UV region. This is then absorbed by a phosphor and reradiated in the visible region. The luminous efficacy and colour properties of induction lamps are similar to those of fluorescent lamps, their main advantage being the longer life produced by not having any electrodes to fail.

The other type of electrodeless lamp uses a radio frequency generator focused through a waveguide onto an enclosure to produce a plasma in the enclosure. These are called plasma lamps and are essentially MH lamps. The luminous efficacy and colour properties of plasma lamps are similar to those of MH lamps, their main advantage being the high system efficiency and good lumen maintenance.

1.7.3.9 Light-Emitting Diodes

The LED is a semiconductor that emits light when a current is passed through it. The spectral emission of the LED depends on the materials used to form the semiconductor. For light, the most common LED material combinations are now aluminium indium gallium phosphide (AlInGaP) and indium gallium nitride (InGaN). LEDs typically produce radiation in a narrow, Gaussian-shaped band, the spectral emission being characterized by the wavelength at which the maximum emission occurs (peak wavelength) and the full width half maximum (FWHM) bandwidth, this being the difference in wavelengths at which the radiant flux is half the maximum radiant flux. AlInGaP LEDs have peak wavelengths of 626, 615, 605 and 590 nm, corresponding, respectively, to the perceptions of red, red-orange, orange and amber. InGaN LEDs have peak wavelengths of 525, 505, 498 and 450 nm, corresponding to the perception of green, green-blue, blue-green and blue. The FWHM for LEDs is typically about 25 nm.

The light output of LEDs is determined by the current through the semiconductor and its temperature. Basically, the higher is the current and the lower is the temperature, the higher is the light output. The current is controlled through control gear called a driver. Care should be taken when using LEDs not to exceed the maximum current recommended by the manufacturer. Provided this precaution is taken, LEDs can have a long life of up to 60,000 h. As for luminous efficacy, the latest high-flux LEDs have luminous efficacies up to 100 lm/W and this is increasing rapidly.

It might be thought that the fact that LED is a narrowband source of light would preclude its use for general lighting, apart from the entertainment industry, but this is not the case. There are two methods for producing white light using LEDs. One method is to combine the outputs of three, four or more different LEDs in one luminaire. Then, by applying different currents to the different LEDs, any colour within the shape formed on the CIE chromaticity diagram by the lines connecting the chromaticity coordinates of the individual LEDs can be produced. The number of different LEDs used represents a trade-off between luminous efficacy and colour properties; the greater the number of different LEDs, the lower the luminous efficacy but the better the colour properties. The problem with this approach is that the light output of LEDs with different peak wavelengths decreases at different rates, meaning the colour properties change over time or a complicated feedback system has to be used to stabilize the colour properties.

The other method by which LEDs can create white light is to use an LED-emitting UV or short-wavelength visible radiation to illuminate one or more phosphors that emit light in the rest of the visible range. This approach has the advantage that when multiple LEDs are used to generate enough light output for practical application, illuminating a separate phosphor surface averages out any colour differences between the individual LEDs.

Figure 1.13 shows the spectral emissions of both methods of producing nominally white light. The LED is a rapidly improving light source which looks set to become the dominant light source used both indoors and outdoors, very soon.

1.7.3.10 Others

It should not be thought that the earlier discussion represents all the light sources available. They are simply the light sources most commonly used for general lighting, both indoors and outdoors. There are many forms of each class of light source available together with others still under development and yet others developed for special applications. Among the former are tungsten halogen lamps using dichroic coatings on the envelope to reflect IR radiation back to the filament to maintain the temperature at a lower current. The most interesting light sources under development are organic light-emitting diodes (OLEDs) and polymer light-emitting diodes (PLEDs). These are area light sources that can be printed onto plastic substrates and hence can take up different shapes. As for light sources for special applications, these include cold cathode fluorescent lamps used for advertising and decorative effect and short-arc xenon and MH lamps used in searchlights and for television. Extensive discussions of the more common light sources can be found in the IESNA Lighting Handbook (IESNA, 2011a) and Kitsinelis (2011).

1.7.4 Light Source Characteristics

Electric light sources can be characterized on several different dimensions. They are as follows:

- Luminous efficacy – the ratio of luminous flux produced to electrical power supplied (lm/W). If the lamp needs a ballast or driver to operate, the watts supplied should include the power demand of the ballast or driver. The lamp should also be operated for long enough to reach stable light output.
- Spectral power distribution – the radiant flux (W) emitted at different wavelengths.
- CCT (see Section 1.6.3.1).

TABLE 1.4
A Summary of the Properties of Some Widely Used Electric Light Sources

Light Source	Luminous Efficacy (lm/W)	CCT (K)	CIE General CRI	Lamp Life (h)	Warm-Up Time (Min)	Restrike Time (Min)
Incandescent	8–14	2,500–2,700	100	1,000	Instant	Instant
Tungsten halogen	15–25	2,700–3,200	100	1,500–5,000	Instant	Instant
Tubular fluorescent	20–96	2,700–17,000	50–98	8,000–19,000	0.5	Instant
Compact fluorescent	20–70	2,700–6,500	80–90	5,000–15,000	0.25–1.5	Instant
Mercury vapour	33–57	3,200–3,900	40–50	8,000–10,000	4	3–10
MH	60–98	3,000–6,000	60–93	2,000–10,000	1–8	3–20
HPS	40–142	1,900–2,500	19–83	6,000–20,000	2–7	0–1
LPS	70–180	n.a.	n.a.	15,000–20,000	10–20	1
Induction	47–80	2,550–4,000	80	60,000	1	Instant
White LED	30–100	2,650–6,500	40–85	15,000–60,000	Instant	Instant

- Duv (see Section 1.6.3.1).
- CIE general CRI (see Section 1.6.3.2).
- Lamp life – the number of burning hours until either lamp failure or a stated percentage reduction in light output occurs. Lamp life can vary widely with switching cycle.
- Warm-up time – the time from switch on to full light output.
- Restrike time – the time delay between the lamp being switched off before it will reignite.

Figure 1.13 shows the spectral power distribution of most of the lamp types discussed earlier. Table 1.4 summarizes the other characteristics for many of the same lamp types. The values in Table 1.4 show wide ranges in many of the metrics for the same lamp type. This means that exact details of the characteristics of any specific lamp should always be obtained from the manufacturer.

1.7.5 Artificial Light Sources: Electric/Signs and Signals

Many of the lamp types discussed earlier are also used for internally and externally illuminated signs and signals. For example, incandescent lamps are used in traffic signals; LEDs can be found in both traffic signals and exit signs as well as being used to form addressable message signs; fluorescent lamps and MH lamps are used to externally illuminate road signs; tubular fluorescent lamps are used for externally illuminated billboards and internally illuminated advertising signs; and miniature incandescent lamps and LEDs are used for brake lights and direction indicators on vehicles, as well as for lighting instrument panels. However, there are other light sources that are used primarily for signs and signals alone. The two that will be discussed here are the electroluminescent and radioluminescent light sources.

1.7.5.1 Electroluminescent Lamps

Electroluminescent lamps are a sandwich made up of a flat area conductor, a layer of dielectric–phosphor mixture and another area conductor that is transparent. When a high, alternating voltage is applied across the two area conductors, the phosphor is excited and light is emitted. The colour of the light emitted depends on the dielectric–phosphor combination used and the frequency of the applied voltage. Spectral emissions that are perceived as blue, yellow, green and pink are available. Electroluminescent lamps have luminous efficacies less than incandescent lamps. However, the fact that they have a long life and low power requirements and can be formed as either rigid ceramic or flexible plastic sheets or tapes has made them an attractive option for instrument panels and for backlighting liquid crystal displays.

1.7.5.2 Radioluminescent Lamps

These light sources consist of a sealed glass tube filled with tritium gas and coated with a phosphor. Low-energy beta particles from the tritium are absorbed by the phosphor, which in turn emits light, the spectrum emitted depending on the phosphor used. These lamps require no power supply, so they have an infinitely high luminous efficacy. Unfortunately, they also emit very little light, the luminance of the glass tube being about 2 cd/m^2 (a T5 fluorescent tube has a luminance of about 16,000 cd/m^2). This low light output and the fact that their disposal is closely regulated have limited their use, one common application being for exit signs in situations where maintenance is difficult or where the atmosphere is hazardous, such as on an oil rig.

1.8 CONTROL OF LIGHT DISTRIBUTION

Being able to produce light is only part of what is necessary to produce illumination. The other part is to control the distribution of light from the light source. For daylight, this is usually done by means of windows or skylights, the effect depending on their size, shape, placement, shielding and glass transmittance properties (Tregenza and Wilson, 2011).

An approach used where daylight has to be delivered deep into a building is some form of guidance system. These consist of a collector for gathering sunlight and skylight, a transmitting system using total internal reflection and a distributor of some sort (CIE, 2006a). The most common of these is the tubular daylight guidance system which delivers only daylight to a space. There are also hybrid systems being developed in which electric lighting is contained within the daylight guidance system, making it easier to control electric lighting in response to variations in daylight (Mayhoub and Carter, 2010).

For electric light sources, control of light distribution is achieved by placing the light source in a luminaire. The luminaire also provides electrical and mechanical support as well as thermal management for the light source. The light distribution is controlled by using shielding, reflection, refraction or diffusion, individually or in combination (Simons and Bean, 2000). One factor influencing how the light distribution is controlled is the luminaire luminous efficacy. This is similar to the luminous efficacy of the light source (see Section 1.7.4), but instead of using the light output of the light source, the light output of the luminaire is taken. Another factor in the choice of which method of light control to adopt in a luminaire is the balance desired between the reduction in the luminance of the light source and the precision required in light distribution. Highly specular reflectors can provide precise control of light distribution, but do little to reduce the maximum luminance of the luminaire. Conversely, diffusers make precise control of light distribution impossible but do reduce the maximum luminance of the luminaire. Refractors are an intermediate case. If all else fails, shielding can be used. Other factors to be considered are the size of the light source and the directionality of its emission when outside the luminaire. Small light sources emitting light in all directions allow precise control of light distribution by reflection, large sources do not. Small sources emitting light in narrow beams can be arranged in one luminaire to provide the required light distribution without further shielding, reflection, refraction or diffusion.

Regardless of how it is achieved, the light distribution provided by a specific luminaire is quantified by the luminous intensity distribution. All reputable luminaire manufacturers provide luminous intensity distributions for their products. Further details on the optical principles of luminaire design and the types of luminaires available can be obtained from the IESNA *Lighting Handbook* (IESNA, 2011a).

1.9 CONTROL OF LIGHT OUTPUT

The control of daylight admitted through a window or skylight is usually achieved by mechanical shielding structures, such as light shelves, or by adjustable blinds (Tregenza and Wilson, 2011). Whenever the sun, or a very bright sky, is likely to be directly visible through a window, some form of blind will be required. Blinds can take various forms: horizontal, Venetian, vertical and roller being the most common. Blinds can also be manually operated or motorized either under manual control or under photocell control. Probably, the most important feature to consider when selecting a blind is the extent to which it preserves a view of the outside. Roller blinds that can be drawn down to a position where the sun and/or sky is hidden but the lower part of the window is still open are an attractive option. Roller blinds made of a mesh material can preserve a view through the whole window while reducing the luminance of the view out. Such blinds are an attractive option where the problem is an overbright sky but will be of limited value when a direct view of the sun is the problem. The same applies to low-transmission glass.

An alternative means of controlling the luminance of windows is electrochromic glazing. Electrochromic glazing has a transmittance that can be continuously modulated by the application of a voltage, thereby providing an opportunity for the dimming of daylight to avoid discomfort. The available transmittance covers the range 0.1–0.8 (Mardaljevic and Nabil, 2008). Whether a transmittance of 0.1 is low enough to deal with the discomfort experienced when the sun can be seen through a window has yet to be established.

For electric light sources, control of light output is provided by switching or dimming systems. Switching systems can vary from the conventional manual switch to sophisticated daylight control systems that switch off lamps near to windows when there is sufficient daylight. Time switches are used to switch off all or parts of a lighting installation at the end of the working day. Occupancy sensors are used to switch off lighting when there is nobody in the space. Such switching systems can reduce electricity waste, but they will be irritating if they switch lighting off when light is required and they may shorten lamp life if switching occurs frequently. The factors to be considered when selecting a switching system are whether to rely on a manual or an automatic system and, if it is automatic, how to match the switching to the activities in the space. If your interest is primarily in reducing electricity consumption, a good principle is to use automatic switch off and manual switch on. This principle uses human inertia for the benefit of reducing energy consumption. If you wish to rely on voluntary manual switching of lighting, care should be taken to make the lighting being switched visible from the control panel and to label the switches so that the operator knows which lamps are being switched.

As for dimming systems, these all reduce light output and energy consumption but not necessarily equally. Usually, the reduction in energy consumption is less than the reduction in light output. A different system is required for each lamp type, and some lamp types cannot be dimmed. The factors to consider when evaluating a dimming system are whether the light source can be dimmed, the range over which dimming can be achieved without flicker or the lamp extinguishing, the extent to which the colour properties of the lamp change as the light output is reduced and any effect dimming has on lamp life and energy consumption.

Sophisticated lighting control systems are available for some light sources that allow the user to have a number of preset scenes. These systems use dimming and switching to alter the lighting of a space. They are commonly used in rooms with multiple functions, such as conference rooms or in locations where different atmospheres are desired at different times.

The range of applications of sophisticated lighting control systems has increased dramatically with the availability of large amounts of computer power in small packages and the advent of inexpensive wireless communication, so much so that such systems are beginning to be used in road lighting to reduce light levels when traffic densities are low at night. Further details on the technology and systems used to control light output can be obtained from the IESNA *Lighting Handbook* (IESNA, 2011a).

1.10 SUMMARY

This chapter is concerned with what light is, how it can be measured and how it is produced and controlled. Light is part of the electromagnetic spectrum between 380 and 780 nm. What differentiates this wavelength range from the rest of the electromagnetic spectrum is that the human visual system responds to it. The actual human spectral response has been standardized in an internationally agreed form represented by the CIE standard photopic and scotopic observers. Using the appropriate spectral sensitivity curve, four basic photometric quantities can be derived – luminous flux, luminous intensity, illuminance and luminance.

These measures are all concerned with the overall amount of light and not with its colour. To deal with colour, the two approaches of colour models and the colour atlas are considered. This leads to a description of the CIE colorimetric system, including the 2D chromaticity diagrams and the 3D colour spaces. By using these measures, colour can be quantified and the colour quality of light sources characterized. This is still being done using such measures as CCT and CIE general CRI, but there are a number of alternative measures under development.

Having considered how light can be measured, the physical principles and properties of natural and artificial light sources are described. Natural light is characterized by its variability in both quantity and spectral emission. Artificial light sources are more stable but differ considerably in their properties, particularly light output, spectral content and the efficiency with which they convert electricity to light.

It is important to appreciate that while there are numerous metrics used to characterize a lighting situation or a light source, these metrics are simultaneously precise and inaccurate. The precision arises because the metrics can often be measured or calculated exactly. If they are regarded as simple physical measures, they can be considered accurate. But they are not simple physical measures. The whole reason for having photometric and colorimetric quantities is to quantify the visual effect of light. Because of the complexity and flexibility of the human visual system and the differences between individuals, any one standardized metric of visual effect is inevitably an approximation. The photometric and colorimetric quantities discussed are the best approximations so far devised, but it should always be remembered that they are approximations and their apparent precision can be deceptive.

2 Visual System

2.1 INTRODUCTION

Light is necessary for the human visual system to operate. With light, we can see; without light, we cannot. This chapter describes the structural, operational and perceptual characteristics of the human visual system.

2.2 STRUCTURE OF THE VISUAL SYSTEM

The first thing to appreciate about the visual system is that it is not the eye alone. Rather, it is the eye and brain working together. The visual system is often likened to a camera but this analogy is misleading. The only parts of the visual system that resemble a camera are the optical components of the eye. Once the optical components have formed an image of the world on the retina, the camera analogy fails. All the rest of the visual system is an image-processing system that extracts specific aspects of the retinal image for interpretation by the brain. Despite this fact, the obvious starting point for a consideration of the visual system is the eye.

2.2.1 Visual Field

Humans have two eyes, mounted frontally. This is the classic position of the eyes for a predator, the two frontally mounted eyes providing considerable overlap between the two visual fields and hence the good depth perception necessary to stalk and capture prey. Animals that are prey typically have their eyes mounted laterally so that their visual fields cover a larger portion of the world around them.

Figure 2.1 shows the approximate extent of the visual field of the two eyes in humans and the overlap between them. Given the limited field of view imposed by the frontal mounting of the two eyes, it is necessary for the two eyes to be able to move. There are two ways this can be done: by moving the head and by moving the eyes in the head. Most animals do both, although some creatures show a bias to one extreme or the other. Owls, for example, have very limited ability to move their eyes but can move their heads over a wide range. Humans have a more limited range of head movements but a wide range of eye movements.

2.2.2 Eye Movements

Figure 2.2 shows the muscles used to adjust the position of the eye in its socket. There are six extraocular muscles arranged in opposing pairs. Each muscle is attached to the wall of the eye cavity in the skull, so that when opposing pairs of muscles are contracted and relaxed, the eye moves. There are several different types of eye movements. When trying to stare directly at a target, without moving the eyes, a process

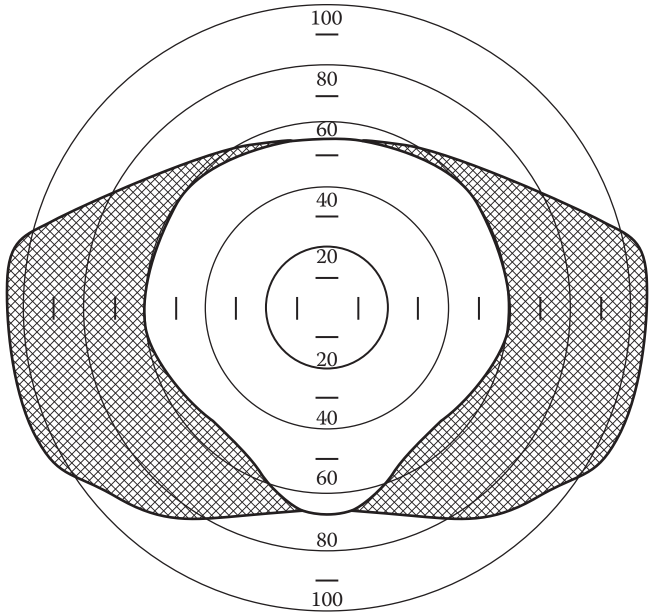

FIGURE 2.1 The binocular visual field expressed in degrees deviation from the point of fixation. The shaded areas are visible to only one eye. (After Boff, K.R. and Lincoln, J.E., *Engineering Data Compendium: Human Perception and Performance*, Harry G. Armstrong Aerospace Medical Research Laboratory, Wright-Patterson AFB, OH, 1988.)

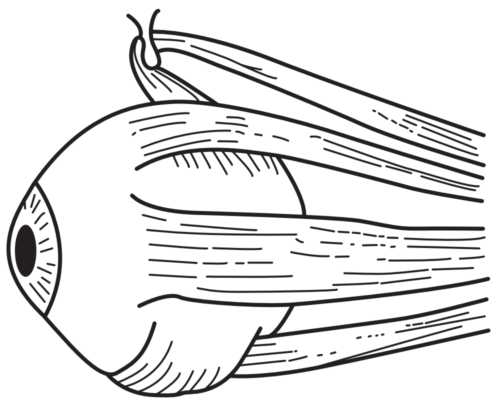

FIGURE 2.2 The arrangement of the muscles used to move the eye.

called fixation, three types of eye movement occur. Tremor, a small oscillation in the eye position, is always present. It might be thought that tremor is the outcome of noise in the eye position control system and has no other significance, but when tremor is eliminated by an optical feedback system, vision rapidly fails, a structured visual field degrading into a uniform field (Pritchard et al., 1960). Therefore, tremor of the retinal image is essential for the visual system to operate.

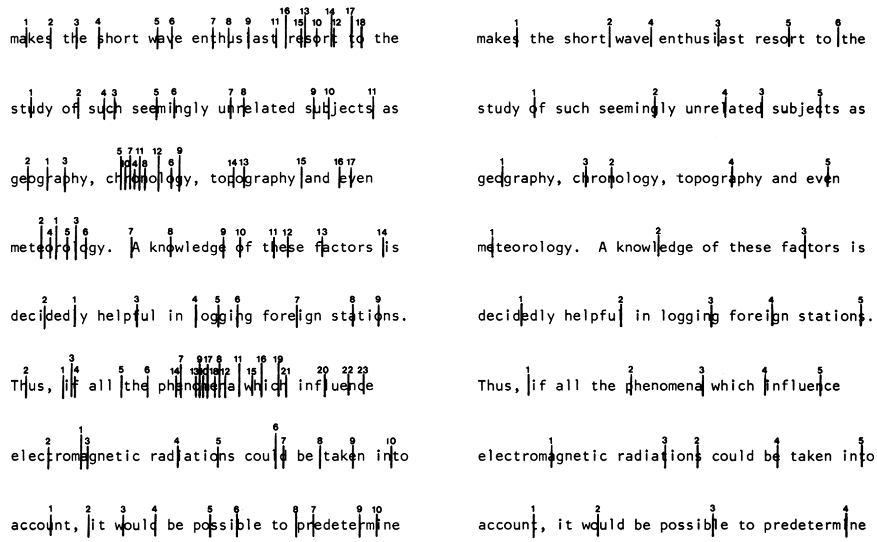

FIGURE 2.3 The patterns of fixations made by two readers reading the same passage. The intersection of a vertical line with the line of print indicates a fixation point. The numbers attached to the vertical lines give the order in which the fixations occurred for each line of print. The reader on the right has a more extensive vocabulary than the reader on the left. (After Buswell, G.T., *How Adults Read*, Supplementary Adult Monograph 45, University of Chicago, Chicago, IL, 1937.)

During fixation, the eye tends to drift slowly away from the fixation point, but eventually, fixation is restored by a rapid jump movement called a saccade. Saccades are very fast, velocities ranging up to 1000°/s depending upon the distance moved. Saccadic eye movements have a latency of about 200 ms, which limits how frequently the line of sight can be moved to about five movements per second. Visual functions are substantially limited during saccadic movements. Figure 2.3 shows a pattern of fixations for people reading text. Movement between the fixation points is made by saccades.

About the only situation in which saccades rarely occur is in smooth pursuit eye movements. Such movements are relatively slow, up to 40°/s, and occur when trying to track a smoothly moving object, for example, a commercial aircraft in flight. Given a smoothly moving stimulus, the visual system can produce a smooth pursuit eye movement. The pursuit system cannot follow smoothly moving targets at high velocities or slower but erratically moving targets such as a bat in flight.

These eye movements all occur in a single eye, but movements in the two eyes are not independent. Rather, they are coordinated so that the lines of sight of the two eyes are both pointed at the same target at the same time. If the lines of sight of the two eyes are not aimed at the same target at the same time, the target may be seen as double (diplopia). Movements of the two eyes in the same direction so as to keep the primary lines of sight converged on a target are called version movements. Movements of the two eyes in opposite directions so as to switch fixation from a target at one distance to a new target in the same direction but at a different distance are called vergence movements. Vergence movements are slow, up to 10°/s, but can occur as a jump movement or can smoothly follow a target moving in a fore-and-aft direction. Both version and vergence movements involve a change in the angle between the two eyes.

2.2.3 Optics of the Eye

Figure 2.4 shows a section through the eye, the upper and lower halves being adjusted for focus at near and far distances, respectively. The eye is basically spherical with a diameter of about 24 mm. The sphere is formed from three concentric layers. The outermost layer, called the sclera, protects the contents of the eye and maintains its shape under pressure. Over most of the eye's surface, the sclera looks white, but at the front of the eye, the sclera bulges up and becomes transparent. It is through this area, called the cornea, that light enters the eye. The next layer is the vascular tunic or choroid. This layer contains a dense network of small blood vessels that provide oxygen and nutrients to the next layer, the retina. Without these supplies, the retina would die. As the choroid approaches the front of the eye, it separates from the sclera and forms the ciliary body. This element produces the watery fluid that lies between the cornea and the lens, called the aqueous humour. The aqueous humour provides oxygen and nutrients to the cornea and the lens and takes away their waste products. Elsewhere in the eye, this is done by blood, but on the optical pathway through the eye, a transparent medium is necessary.

As the ciliary body extends further away from the sclera, it becomes the iris. The iris consists of two layers, an outer layer containing pigment and an inner layer containing blood vessels. The colour of the iris is determined by the extent to which the outer layer is pigmented. If the outer layer is heavily pigmented, the iris will appear brown, but if it is lightly pigmented, the iris will appear to be a colour formed by a combination of the outer and inner layers, usually blue, green or grey. If there is no or very little pigment in the outer layer, as is the case with albinos, the colour of the iris is determined by the inner layer and hence will appear pink.

The iris forms a circular opening, called the pupil, which admits light into the eye. The pupil can be changed in size by the operation of the two sets of muscles, one set that lie around the pupil and another that is directed radially out from the pupil. When the first set of muscles contract, the pupil is decreased in size. When the second set

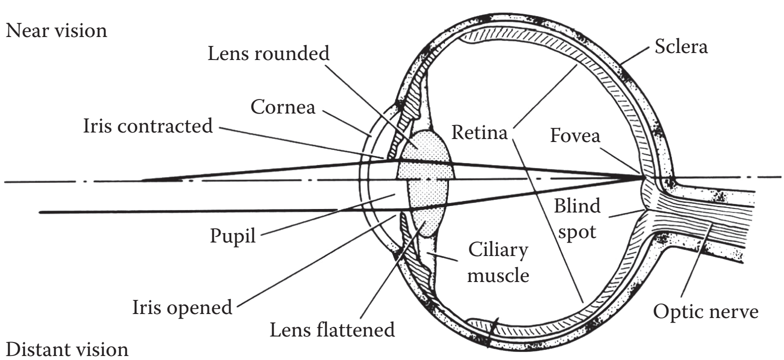

FIGURE 2.4 A section through the eye adjusted for near and distant vision.

contract, the pupil expands. Pupil size varies with the amount of light reaching the retina, but it is also influenced by the distance of the object from the eye, the age of the observer and emotional factors such as fear, excitement and anger (Duke-Elder, 1944).

After passing through the pupil, light reaches the crystalline lens. The lens is fixed in position, but varies its focal length by changing its shape. The change in shape is achieved by contracting or relaxing the ciliary muscle. For objects close to the eye, the lens is fattened. For objects far away, the lens is flattened.

The space between the lens and the retina is filled with another transparent material, the jelly-like vitreous humour. After passing through the vitreous humour, light reaches the retina, the location where light is absorbed and converted to electrical signals. The central part of the retina is covered by the macula, a transparent yellow filter with a diameter of 5 mm. The role of the macula is to protect the most important part of the retina from short-wavelength visible and ultraviolet (UV) radiation.

The retina itself is a complex structure, as can be seen from Figure 2.5, which shows a section through it. It can be considered as having three layers: a layer of

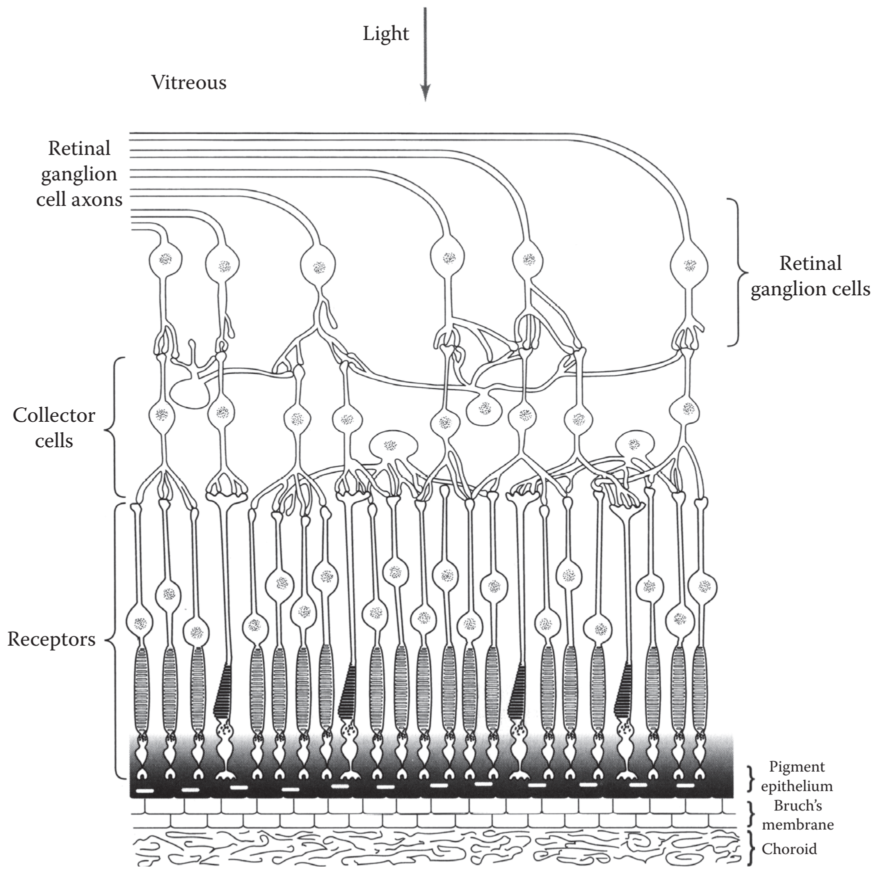

FIGURE 2.5 A section through the retina. (After Sekular, R. and Blake, R., *Perception*, 3rd edn., McGraw-Hill, New York, 1994.)

visual photoreceptors that can be divided into four types, a layer of collector cells that provide links between multiple photoreceptors and a layer of ganglion cells, a few of which are photosensitive and feed the non-image-forming system (see Section 3.2). The axons of the ganglion cells form the optic nerve which produces the blind spot where it passes through the retina out of the eye. Light reaching the retina passes through the ganglion and collector cell layers before reaching the visual photoreceptors. Any light that gets past the visual photoreceptor layer is absorbed by the pigment epithelium except for a small fraction which is reflected to form stray light within the eye.

2.2.4 Structure of the Retina

The retina is an extension of the brain. It derives from the same tissue as the brain, and like the brain, damaged cells are not replaced. The visual system has four visual photoreceptor types in the retina, each containing a different photopigment. These four types are conventionally grouped into two classes, rods and cones, these names being derived from their appearance under a microscope. All the rod photoreceptors are the same, containing the same photopigment, rhodopsin, and hence having the same spectral sensitivity. The relative spectral sensitivity of the rod photoreceptors is shown in Figure 2.6. The other three photoreceptor types are all cones, each with a different photopigment. Figure 2.7 shows the relative spectral sensitivity functions of the three cone photoreceptor types called short-, medium- and long-wavelength cones (S-, M- and L-cones) after the wavelengths where they have the greatest sensitivity (450, 525 and 575 nm, respectively).

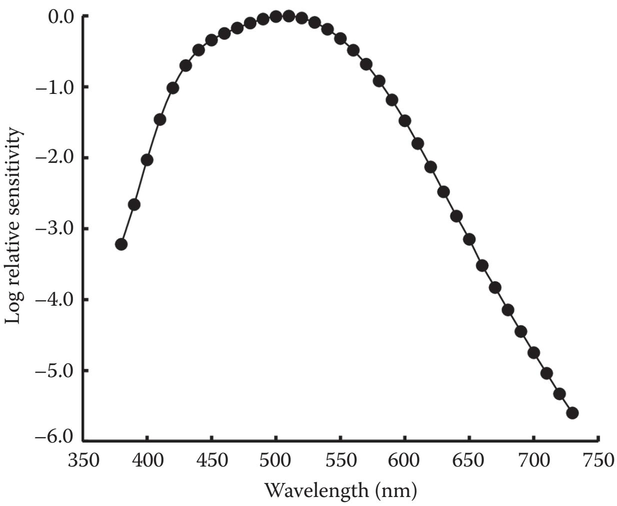

FIGURE 2.6 The log relative spectral sensitivity of the rod photoreceptor. (After Commission Internationale de l'Eclairage (CIE), *CIE 1988 2° Spectral Luminous Efficiency Function for Photopic Vision*, CIE Publication 86, CIE, Vienna, Austria, 1990.)

Rods and cones are distributed differently across the retina (Figure 2.8). The cones are concentrated in one small area that lies on the visual axis of the eye, called the fovea, although there is a low density of cones across the rest of the retina. There are no rod photoreceptors at the centre of the fovea, the greatest concentration of rods occurring at about 20° eccentricity from the fovea.

The three cone types are also not distributed equally across the retina. The L- and M-cones are concentrated in the fovea, their density declining gradually with

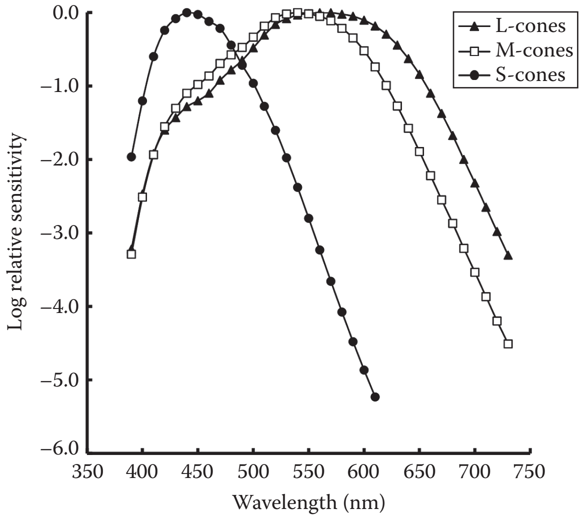

FIGURE 2.7 The log relative spectral sensitivities of long- (L), medium- (M) and short-wavelength (S) cone photoreceptors. (After Kaiser, P.K. and Boynton, R.M., *Human Color Vision*, Optical Society of America, Washington, DC, 1996.)

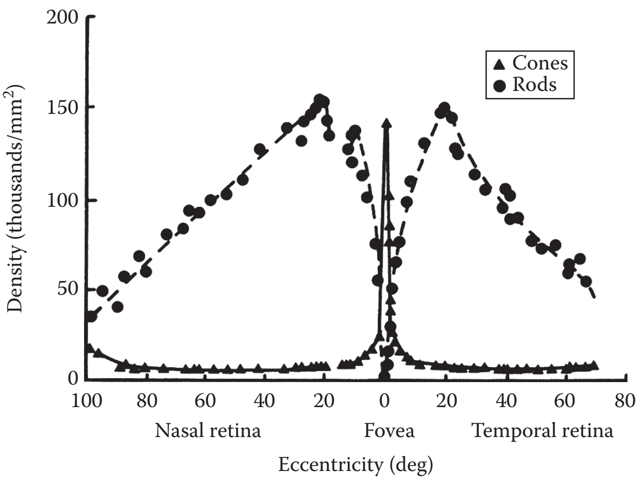

FIGURE 2.8 The distribution of rod and cone photoreceptors across the retina. The 0° indicates the position of the fovea.

increasing eccentricity. The S-cones are largely absent from the fovea, reach a maximum concentration just outside the fovea and then decline gradually in density with increasing eccentricity. The ratio of the L-, M- and S-cone types in and around the fovea is approximately 32:16:1 (Walraven, 1974).

Over the whole retina, there are many more rods than cones, approximately 110 million rods and 5 million cones. The fact that there are many more rod than cone photoreceptors should not be taken to indicate that human vision is dominated by the rods. It is the fovea that allows resolution of detail and other fine discriminations and the fovea is dominated by cones. There are three other anatomical features that emphasize the importance of the fovea. The first is the absence of blood vessels. For most of the retina, light passes through a network of blood vessels before reaching the photoreceptors, but blood vessels avoid crossing over the central area of the fovea, called the foveola. The foveola has a diameter of about 0.3 mm. The second is the fact that even the collector and ganglion layers of the retina are pulled away over the fovea. This thins the layers immediately above the foveola and helps reduce the absorption and scattering of light, thereby enhancing the resolution of detail. The third is the fact that the outer limb of the cone photoreceptor can act as a waveguide, so a photon of light arriving along the cone axis is much more likely to be absorbed than one arriving at an angle to the cone axis. This directional sensitivity, known as the Stiles–Crawford effect (Crawford, 1972), compensates to some extent for the poor quality of the eye's optics by making the fovea less sensitive to stray or scattered light. Rod photoreceptors, which dominate the population of the retina outside the fovea, do not show a Stiles–Crawford effect.

2.2.5 Functioning of the Retina

The retina is where the processing of the retinal image begins. Recordings of electrical output from single ganglion cells in the retinas of monkeys and cats, creatures that have visual systems similar to those of humans, have shown a number of important characteristics of the operation of the retina. The first is the fact that the electrical discharge is a series of voltage spikes of equal amplitude. Variations in the amount of light falling on the visual photoreceptors supplying signals to the ganglion cells through the network of collector cells produce changes in the frequency with which these voltage spikes occur but not in their amplitude. The second is that there is a electrical discharge present even when there is no light falling on the visual photoreceptors, called the spontaneous discharge. The third is that illuminating visual photoreceptors with a spot of light can produce either an increase or a decrease in the frequency of electrical discharges, relative to the frequency of discharges present when light is absent.

Further studies of the pattern of electrical discharges from a single ganglion cell have revealed two other important aspects of the operation of the retina. The first is the existence of receptive fields. A receptive field is the area of the retina that determines the output from a single ganglion cell. The size of a receptive field is measured by exploring the retina with a very small spot of light while measuring the electrical discharges from the ganglion cell. The boundary of the receptive field is determined by the point beyond which applying the spot of light fails to alter the spontaneous electrical discharge from the ganglion cell.

A given receptive field always represents the activity of a number of visual photoreceptors and often reflects input from different cone types as well as from rods. The sizes of receptive fields vary systematically with retinal location. Receptive fields around the fovea are very small. As eccentricity from the fovea increases, so does receptive field size.

The sensitivity of a receptive field to light is primarily determined by its size. Because all ganglion cells require some minimum electrical input to be stimulated, a receptive field that receives input from a large number of visual photoreceptors can be stimulated by a lower retinal irradiance than can a receptive field which receives input from only a few visual photoreceptors. Hence, the sensitivity to light of small receptive fields is usually significantly less than that of larger fields. The rod photoreceptors, which are concentrated outside the fovea, are organized into relatively large receptive fields. This combination of large receptive fields, relatively low spontaneous discharge levels and longer integration times makes the rod photoreceptor system significantly more sensitive to light than the cone photoreceptor system.

Within each ganglion cell receptive field, there is a specific structure. Again, by recording the electrical discharges from a ganglion cell and exploring within a receptive field with a very small spot of light, it has been found that retinal receptive fields consist of a central circular area and a surrounding annular area. These two areas have opposing effects on the ganglion cell's electrical discharge. Either the central area increases and the annular surround decreases the rate of electrical discharge or, in other receptive fields, the reverse occurs. These types of receptive fields are known as on-centre/off-surround and off-centre/on-surround fields, respectively. If either of these two types of retinal receptive fields is illuminated uniformly, the two types of effect on electrical discharge cancel each other, a process called lateral inhibition. However, if the illumination is not uniform across the two parts of the receptive field, a net effect on the ganglion cell discharge is evident. This pattern of response makes the receptive fields well suited to detect boundaries in the retinal image. There are an approximately equal number of on-centre/off-surround and off-centre/on-surround receptive fields in the retina. The electrical signals from the two types of receptive field do not cancel each other. Rather, the signals from the two types of receptive field are kept separate, indicating that they serve different aspects of vision.

While every retinal ganglion cell feeding the visual system has a receptive field, not every such ganglion cell is the same. In fact, there are three types of ganglion cell called magnocellular (M) cells, parvocellular (P) cells and koniocellular (K) cells. There are a number of important differences between these cells. First, the axons of the M-cells are thicker than the axons of the P- or K-cells, indicating that signals are transmitted more rapidly from the M-cells than from the P- or K-cells. Second, there are many more P- than M-cells and many more M- than K-cells, and they are distributed differently across the retina. The P-cells dominate in the fovea and parafovea and the M-cells dominate in the periphery. The K-cells are located outside the fovea. Third, the three cell types are sensitive to different aspects of the retinal image. The M-cells are more sensitive to rapidly varying stimuli and to small differences in luminance but are insensitive to differences in colour. The P- and K-cells are sensitive to colour; the P-cells receive input from the L- and M-cones, while the K-cells receive input from the S-cones.

Overall, this very brief description of the retina should have demonstrated that the retina is really the first stage of an image-processing system. The retina extracts information on boundaries in the retinal image and then extracts specific aspects of the stimulus within the boundaries, such as colour. These aspects are then transmitted up the optic nerve, formed from the axons of the retinal ganglion cells, along different channels.

2.2.6 Central Visual Pathways

Figure 2.9 shows the pathways over which signals from the retina are transmitted to the visual cortex. The optic nerves leaving the two eyes are brought together at the optic chiasm, rearranged and then extended to the lateral geniculate nuclei (LGN). Somewhere between leaving the eyes and arriving at the LGN, some optic nerve fibres are diverted to the superior colliculus, located at the top of the brain stem and responsible for controlling eye movements, to the brain stem nuclei that control pupil size as well as to other parts of the brain concerned with non-visual aspects of human physiology (see Chapter 3). As for vision, after the LGN, the two optic nerves spread out to supply information to various parts of the visual cortex, the part of the brain where vision occurs.

At the optic chiasm, the optic nerve from each eye is split and then parts of the optic nerves from the same side of the two eyes are combined. This arrangement ensures that the signals from the same side of the two eyes are received together on the same side of the visual cortex.

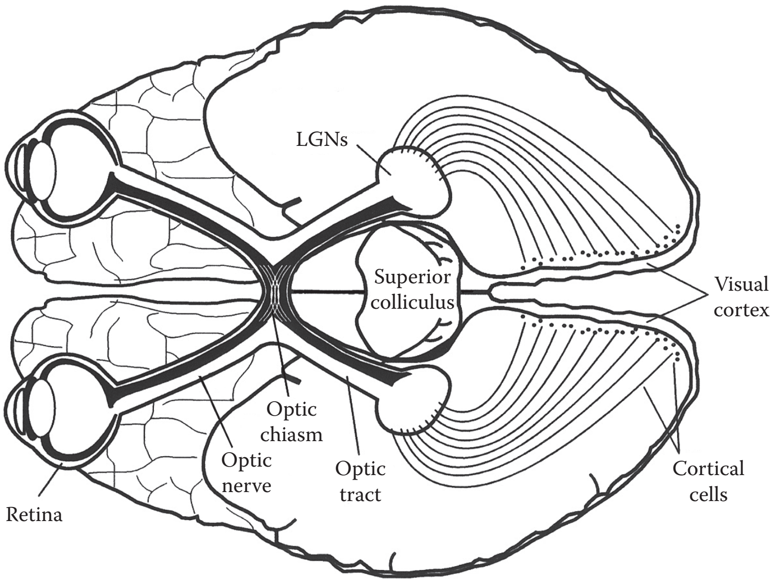

FIGURE 2.9 A schematic diagram of the pathways from the eyes to the visual cortex. (From Illuminating Engineering Society of North America (IESNA), *The Lighting Handbook*, 9th edn., IESNA, New York, 2000a.)

The signals from the same side of the two eyes pass from the optic chiasm to an LGN. Anatomically, an LGN shows six distinct layers. Two of these layers receive signals from the M-ganglion cells of the retina, while the other four layers receive signals from the P-ganglion cells. Between each of these layers is another thin layer that receives signals from the K-ganglion cells. Each layer is arranged so that the location of the ganglion cells on the retina is preserved. In other words, each layer preserves a map of the retina. As in the retina, electrophysiological recording of discharges from individual LGN cells has shown the existence of receptive fields, with either on-centre/off-surround or off-centre/on-surround. The division of function found in the retina is also present in the LGN. The M layers respond to movement but not to colour differences, but the P and K layers do respond to colour differences. Indeed, some receptive fields show strong responses when the centre is illuminated by one colour and the surround by another. The specific colour combinations are red and green or yellow and blue, these being the basis of human colour vision (see Section 2.2.7). The receptive fields in the P layers are smaller than in the M layer, so the P layer will be better at resolving detail; but the M layer will respond faster to a change in the amount of light. The functions of the K layer are still the subject of study.

From the above description, it might seem that the LGN are just relay stations between the retinas of the two eyes and the visual cortex. However, they are more than this. The LGN also receive signals from the reticular activating system, a part of the brain stem that determines the general level of arousal, as well as signals descending from the cortex and from other regions of the brain. Clearly, the LGN are involved in the interaction of other senses and assumptions about incoming visual information.

The visual cortex is located at the back of cerebral hemispheres. It consists of another layered array, containing about one million or so cells. Apart from its amazing complexity, what is remarkable about it is the similarity of its organization to the organization of the retina and the LGN. For example, the M, P and K channels remain separated, signals from the different layers of the LGN being received in different layers of the visual cortex. Further, each cortical cell reacts only to signals from a limited area of the retina, and the arrangement of the cortical cells replicates the arrangement of ganglion cells on the retina. Moreover, the number of cortical cells allocated to each part of the retina enhances the importance of the fovea. About 80% of the cortical cells are devoted to the central 10° of the visual field (Drasdo, 1977), the centre of which is the fovea, a phenomenon called cortical magnification. As for how the cortical cells respond to light stimulation, again, on-centre/off-surround and off-centre/on-surround cells are found, but now they show sensitivity to the orientation of a boundary. Other cells do not show a clear on/off structure but are still sensitive to the orientation of a boundary and will respond strongly to a moving boundary of the appropriate orientation. There are also cortical cells grouped together that show no sensitivity to boundary orientation but are very sensitive to colour differences. Yet other cells respond more to signals from the left eye and others to the right eye, while some respond equally to signals from both eyes. All this cellular diversity occurs at the entry level of the visual cortex. There is a much more complex structure beyond this in the higher areas of the visual cortex (Purves and Beau Lotto, 2003). Investigation of these areas has shown that different parts of the visual cortex are dedicated to specific discriminations. For example, areas have been identified in the visual cortex that are concerned with analysing colour, motion and even human faces viewed from particular angles (Desimone, 1991).

2.2.7 Colour Vision

So far, this consideration of the structure of the human visual system has not considered the perception of colour. Human colour vision is trichromatic, that is, it is based on the three different cone photoreceptors. These photoreceptors are characterized by having different wavelengths for peak sensitivity, but all have a broad spectral sensitivity and show considerable overlap (Figure 2.7). The number of photoreceptor types used to form a colour system is a matter of compromise. A single photoreceptor type containing a single photopigment is unable to discriminate differences in wavelength from differences in irradiance and so does not support colour vision, for example, rod photoreceptors. A system with many different photoreceptors each containing a different photopigment would be able to make many discriminations between wavelengths but at the cost of taking up more of the neural capacity of the visual system. Studies of the spectral emission of typical light sources have shown that trichromacy provides an accurate description of surface colours under most lighting conditions (Lennie and D'Zmura, 1988).

Figure 2.10 shows how the outputs from the three cone photoreceptor types are arranged into one non-opponent achromatic system and two opponent

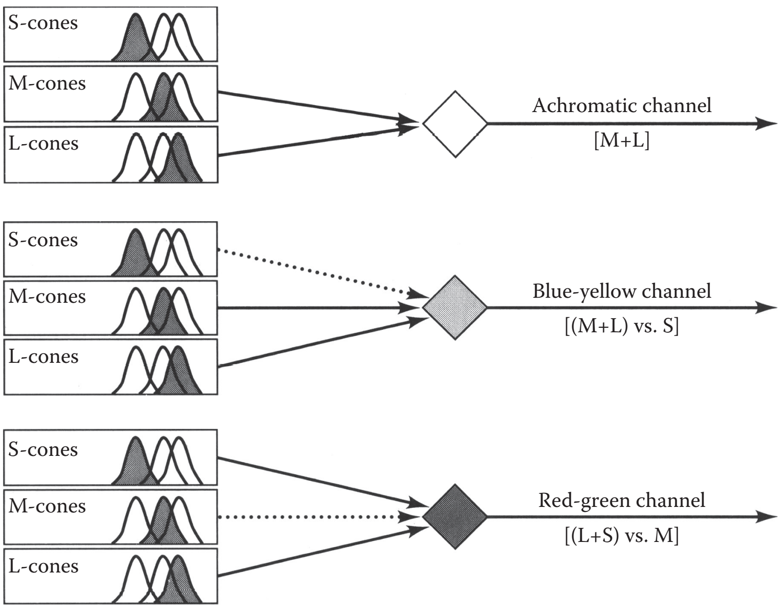

FIGURE 2.10 The organization of the human colour system showing how the three cone photoreceptor types feed into one achromatic, non-opponent channel and two chromatic, opponent channels. (After Sekular, R. and Blake, R., *Perception*, 3rd edn., McGraw-Hill, New York, 1994.)

chromatic systems. The achromatic channel receives inputs from the M- and L-cones only. The red-green opponent channel produces the difference between the output of the M-cones and the sum of the outputs of the L- and S-cones. The other opponent channel, the blue-yellow channel, produces the difference between the S-cones and the sum of the M- and L-cones. This opponent structure for colour vision influences the perception of colours. This was shown in an experiment by Boynton and Gordon (1965). They presented monochromatic lights of different wavelengths and asked subjects to describe the appearance of each stimulus using only the colour names – red, green, yellow and blue. Either one or two names could be used for each colour presented. The interesting result was that people very rarely described a colour as red-green or yellow-blue, while yellow-red and green-blue were frequently used. Even 4-month-old infants divide incident light into four categories, corresponding to what adults call red, yellow, green or blue (Bornstein et al., 1976).

Physiologically, the outputs from the three different cone types are organized into opponent and non-opponent classes in the retina. Outputs in the non-opponent class always give an increase in activity with increasing retinal irradiance, although the magnitude of that increase will vary with the wavelength of the incident light. Outputs in the opponent class can show either an increase or a decrease in activity depending on the wavelength of the incident light. Cells of the non-opponent type constitute the achromatic channel shown in Figure 2.10, while cells of the opponent type form the opponent channels. The achromatic information is transmitted to the visual cortex by the M channel, while the chromatic information proceeds via the P and K channels (Solomon and Lennie, 2007).

The ability to discriminate the wavelength content of incident light makes a dramatic difference to the information that can be extracted from a scene. Creatures with only one type of photopigment, that is, creatures without colour vision, can only discriminate shades of grey, from black to white. Approximately 100 such discriminations can be made. Having two photopigment types increases the number of different combinations of irradiance and spectral content that can be discriminated to about 10,000. Having three types of photopigment increases the number of discriminations to approximately 1,000,000 (Neitz et al., 2001). Thus, colour vision is a valuable part of the visual system and not a luxury that adds little to utility (Mollon, 1989).

Unfortunately, a significant minority of people have defective colour vision, a condition characterized by abnormal colour matching or colour confusions. People with defective colour vision are classified into three categories: monochromats, dichromats and anomalous trichromats, according to the number of visual photoreceptors present and the nature of the photopigments present in those photoreceptors. Monochromats, although very rare, occur in two forms: rod monochromats, where there are no cone photoreceptors, only rod photoreceptors, and cone monochromats, where there are rod photoreceptors and only one type of cone photoreceptor, usually the S-cone. Rod monochromats are truly colour-blind and see only differences in brightness. Cone monochromats have a very limited form of colour vision in the luminance range where both rod and S-cone photoreceptors are operating. Both dichromats and anomalous trichromats have some perception of colour, although not the same perception as people with normal colour vision (for illustrations of how dichromats perceive colours, see McIntyre, 2002). Dichromats have two cone photoreceptors. They see a more limited range of colours than people with normal colour vision and have a different spectral sensitivity, depending on which cone photoreceptor is missing (Wyszecki and Stiles, 1982). Dichromats with the L-cones missing are called protanopes. Dichromats with the M-cones missing are called deuteranopes, while dichromats with S-cones missing are called tritanopes. Anomalous trichromats have all three cone photopigments present, but one of the cones contains a photopigment that does not have the usual spectral sensitivity. Anomalous trichromats who have a defective long-wavelength photopigment are called protanomalous. Anomalous trichromats who have a defective medium-wavelength photopigment are called deuteranomalous, while anomalous trichromats who have a defective short-wavelength photopigment are called tritanomalous. The colour vision of anomalous trichromats can vary widely from almost as bad as a dichromat to little different from someone with normal colour vision.

Overall, about 8% of males and 0.4% of females have some form of defective colour vision; about half being deuteranomalous. Steward and Cole (1989) surveyed people with defective colour vision and found that many such people have some trouble with everyday tasks, such as selecting coloured merchandise and judging the ripeness of fruit (see Table 2.1). Defective colour vision is usually inherited, although it can also be acquired through age, disease, injury or exposure to some

TABLE 2.1
Percentage of People with Different Types of Colour Vision Reporting Difficulties with Everyday Tasks

Activity	Dichromats (%)	Anomalous Trichromats (%)	Normal (%)
Selecting clothes, cosmetics, etc.	86	66	0
Distinguishing the colours of wires, paints, etc.	68	23	0
Identifying plants and flowers	57	18	0
Determining when fruits and vegetables are ripe, by colour	41	22	0
Determining when meat is cooked, by colour	35	17	0
Difficulties in participating in or watching sports because of colour	32	18	0
Adjusting the colour balance of a television satisfactorily	27	18	2
Recognizing skin conditions such as a rash or sunburn	27	11	0
Taking the wrong medication because of difficulties with colour	0	3	0

Source: After Steward, J.M. and Cole, B.L., *Optom. Vis. Sci.*, 66, 288, 1989.

chemicals. There is little that can be done to overcome the limitations of defective colour vision, although filters can sometimes be used to enhance specific colour differences (McIntyre, 2002).

2.2.8 Conclusions

Much remains to be done before the visual system will be completely understood, but what is clear is that the visual system consists of two parts: an optical system that produces an image on the retina of the eye and an image-processing system that extracts different aspects of that image at various stages of its progress from the retina to the visual cortex while preserving the location of the information. In the visual cortex, this diverse information is assembled into a model of the outside world influenced by previous experience.

It is also clear that the visual system devotes most of its resources to analysing the central area of the retina, particularly the fovea. This implies that peripheral vision is mainly devoted to identifying something that should be examined in detail by turning the head and eyes so the image of whatever it is falls on the fovea. One other point that should be appreciated is that the visual system is capable of making long-term adjustments to changed circumstances, both mechanically and neurally (Hofner and Williams, 2002). Specifically, following the removal of a cataract (see Section 13.4), the foveal cone photoreceptors have been shown to realign their main axis from pointing at the edge of the pupil to pointing at the centre; and prolonged exposure to a coloured environment has been shown to produce a shift in the perception of colours so as to compensate for the chromatically altered environment. These adjustments take place over many days and occur under rather extreme circumstances, but the visual system also makes continuous adjustments over much shorter times under normal conditions. These will be discussed next.

2.3 CONTINUOUS ADJUSTMENTS OF THE VISUAL SYSTEM

2.3.1 Adaptation

The human visual system can process information over an enormous range of luminances (about 12 log units), but not all at once. It continually adjusts itself to the prevailing conditions, aiming at reduced sensitivity and finer discrimination when there is plenty of light available and enhanced sensitivity and coarser discrimination when light is in short supply. When the visual system is adapted to a given luminance, much higher luminances appear as glaringly bright, while much lower luminances are seen as black shadows. Figure 2.11 indicates the approximate limits within which differences in luminance can be discriminated for different adaptation luminances. An everyday example of this change in perception is the appearance of a vehicle headlight by day and night. The headlight has the same luminance under both conditions, but as the adaptation luminance decreases as night falls, the brightness of the headlight increases until if viewed directly, it is glaringly bright.

To cope with the wide range of retinal illuminations to which it might be exposed, from a very dark night (0.0001 cd/m^2) to a sunlit beach (20,000 cd/m^2), the visual

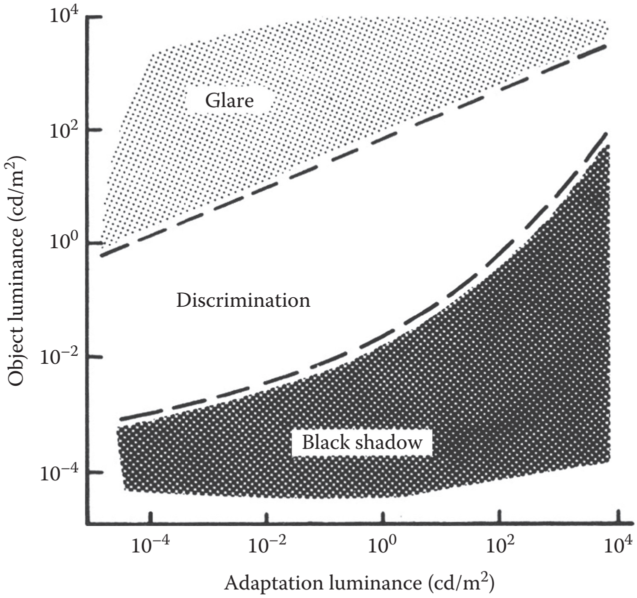

FIGURE 2.11 A schematic illustration of the range of object luminances within which discrimination is possible for different adaptation luminances. The boundaries are approximate. (After Hopkinson, R.G. and Collins, J.B., *The Ergonomics of Lighting*, McDonald & Co., London, U.K., 1970.)

system changes its sensitivity through a process called adaptation. Adaptation is a continuous process involving three distinct changes:

Change in pupil size: The iris constricts and dilates in response to increased and decreased levels of retinal illumination. For young people, the diameter of the pupil can range from about 2 to 8 mm. For older people, the range is less (see Figure 13.2). The amount of light transmitted through the pupil is proportional to its area, so a range of diameters from 2 to 8 mm implies a maximum effect of pupil changes of 16:1. As the visual system can operate over a range of about 1,000,000,000,000:1, this indicates that the pupil plays only a minor role in the adaptation of the visual system. Iris constriction is faster (about 0.3 s) than dilation (about 1.5 s).

Neural adaptation: This is a fast (less than 200 ms) change in sensitivity produced by synaptic interactions in the retina. Neural processes account for virtually all the transitory changes in sensitivity of the eye at luminance values commonly encountered in electrically lighted environments, that is, below luminances of about 600 cd/m^2. The facts that neural adaptation is fast, operates at moderate light levels and is effective over a luminance range of 2–3 log units explain why it is possible to look around most lit interiors without being conscious of being misadapted.

Photochemical adaptation: The four types of visual photoreceptors in the retina contain four different pigments. When light is absorbed, the pigments break down into an unstable aldehyde of vitamin A and a protein (opsin). In the dark, the pigment is regenerated and is again available to absorb light. The sensitivity of the eye to light is largely a function of the percentage of unbleached pigment. Under conditions of steady retinal irradiance, the concentration of photopigment produced by the competing processes of bleaching and regeneration is in equilibrium. When the retinal irradiance is changed, pigment is bleached and regenerated so as to re-establish equilibrium. Because the time required to accomplish the photochemical reactions is of the order of minutes, changes in the sensitivity can lag behind the irradiance changes. The cone photoreceptors adapt much more rapidly than do the rod photoreceptors; even after exposure to high irradiances, the cones will achieve their maximum sensitivity in 10–12 min, while the rods will require 60 min (or longer) to achieve their maximum sensitivity. This is evident in Figure 2.12, which shows the time taken to reach maximum sensitivity, also known as complete dark adaptation.

Exactly how long it takes to adapt to a change in retinal illumination depends on the magnitude of the change, the extent to which it involves different visual photoreceptors and the direction of the change. For changes in retinal illumination of about 2–3 log units, neural adaptation is sufficient, so adaptation should be complete in less than a second. For larger changes, photochemical adaptation is necessary.

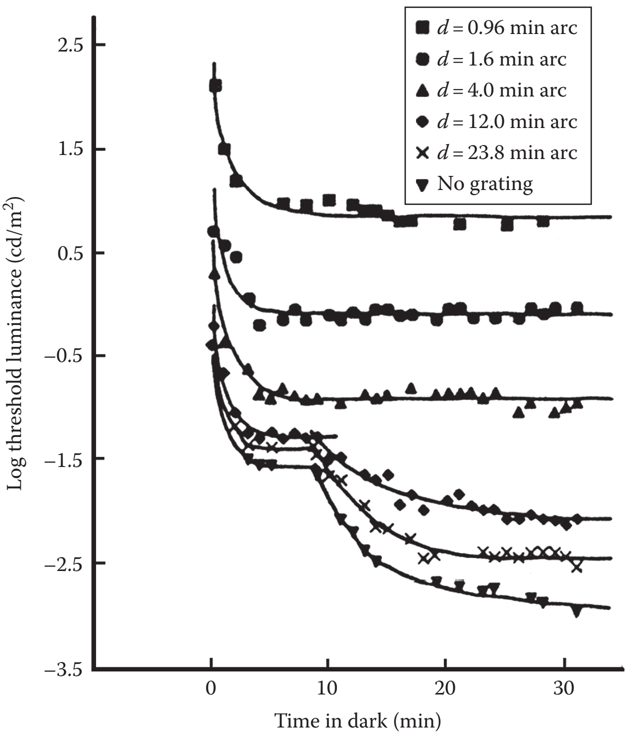

FIGURE 2.12 Log threshold luminances for the resolution of square-wave gratings of bar widths from 0.96 to 23.8 min arc and for detecting a uniform target (no grating), plotted against time in the dark. The luminance to which the subjects were initially adapted was 5011 cd/m^2. (After Brown et al., *J. Opt. Soc. Am.*, 43, 197, 1953.)

If the change in retinal illumination lies completely within the range of operation of the cone photoreceptors, a few minutes will be sufficient for adaptation to occur. If the change in retinal illumination ranges from cone photoreceptor operation to rod photoreceptor operation, tens of minutes may be necessary for adaptation to be completed. As for the direction of change, once the photochemical processes are involved, changes to a higher retinal illuminance can be achieved much more rapidly than changes to a lower retinal illuminance.

When the visual system is not completely adapted to the prevailing retinal illumination, its capabilities are limited (Boynton and Miller, 1963). This state of changing adaptation is called transient adaptation. Transient adaptation is unlikely to be noticeable in interiors in normal conditions but can be significant where sudden changes from high to low retinal illumination occur, such as on entering a long road tunnel on a sunny day or in the event of a power failure in a windowless building.

The usual way of describing the state of adaptation is as the luminance of the visual field to which the observer is adapted. In the laboratory, this is perfectly acceptable. The experimenter can determine the visual field and ensure that it is uniform in a luminance. In this situation, there is little doubt about what the adaptation luminance is. In the real world, determining the adaptation luminance is not so easy. If the observer has one fixation point, such as might be the case for a driver approaching a tunnel entrance by day, then the luminance distribution about the fixation point can be weighted to get a reasonable estimate of the adaptation luminance (Adrian, 1987). If the observer has many fixation points, that is, the observer is moving his or her eyes around a lot, then the average luminance of the whole scene is a good estimate. There are no clear rules for determining the adaptation luminance. The best that can be done is to look at the pattern of fixation points and the time spent at each to get a crude estimate for the adaptation luminance.

2.3.2 Photopic, Scotopic and Mesopic Vision

This process of adaptation can change the spectral sensitivity of the visual system because at different retinal illuminances, different combinations of visual photoreceptors are operating. The three states of sensitivity are conventionally identified as follows:

Photopic vision: This state of the visual system occurs at adaptation luminances higher than approximately 5 cd/m^2. For these luminances, the retinal response is dominated by the cone photoreceptors. This means that both colour vision and fine resolution of detail are available.

Scotopic vision: This operating state of the visual system occurs at adaptation luminances less than approximately 0.005 cd/m^2. For these luminances, only the rod photoreceptors respond to stimulation, the cone photoreceptors being insufficiently sensitive to respond to the low level of retinal irradiance. This means that colour is not perceived, only shades of grey, and the fovea of the retina is blind. Therefore, in scotopic conditions, what limited resolution of detail there is occurs within a few degrees of the fovea.

Mesopic vision: This operating state of the visual system is intermediate between the photopic and scotopic states, that is, between about 0.005 and 5 cd/m^2. In the

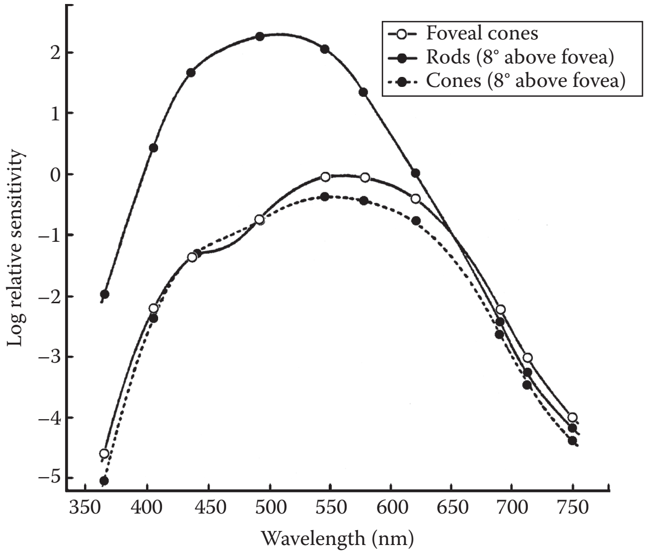

FIGURE 2.13 The log relative spectral sensitivity of dark-adapted foveal and peripheral cone and rod photoreceptors. The spectral sensitivities are all normalized to the maximum sensitivity of the foveal cones. (After Wald, G., *Science*, 101, 653, 1945.)

mesopic state, both cone and rod photoreceptors are active and there are changes in the post-receptoral pathways before the signals from the rod and cone photoreceptors merge. As luminance declines through the mesopic region, the fovea, which is dominated by cone photoreceptors, slowly declines in absolute sensitivity without significant change in spectral sensitivity until vision fails altogether as the scotopic state is reached. In the periphery, the rod photoreceptors gradually come to dominate the cone photoreceptors, resulting in gradual deterioration in colour vision and resolution and a shift in spectral sensitivity to shorter wavelengths.

Figure 2.13 shows the relative sensitivity of rod photoreceptors and the cone photoreceptors in the fovea and outside the fovea. It is clear that the two photoreceptor types differ in sensitivity. The rod photoreceptors are much more sensitive to light than the cone photoreceptors, particularly for short-wavelength radiation.

The relevance of the different operating states for lighting practice varies. Scotopic vision is largely irrelevant. Any lighting installation worthy of the name provides enough light to at least move the visual system into the mesopic state. Most interior lighting ensures that the visual system is operating in the photopic state. Current practice in exterior lighting ensures that the visual system often has to operate in the mesopic state.

The spectral sensitivity of the visual system is different in the photopic, mesopic and scotopic states because different visual photoreceptors are dominant in each state. In the photopic state, cone photoreceptors are dominant everywhere. In the mesopic state, cone photoreceptors are dominant in the fovea, but in the peripheral retina, both rod and cone photoreceptors are active, the balance between them shifting as the retinal irradiance changes. In scotopic conditions, only rod photoreceptors

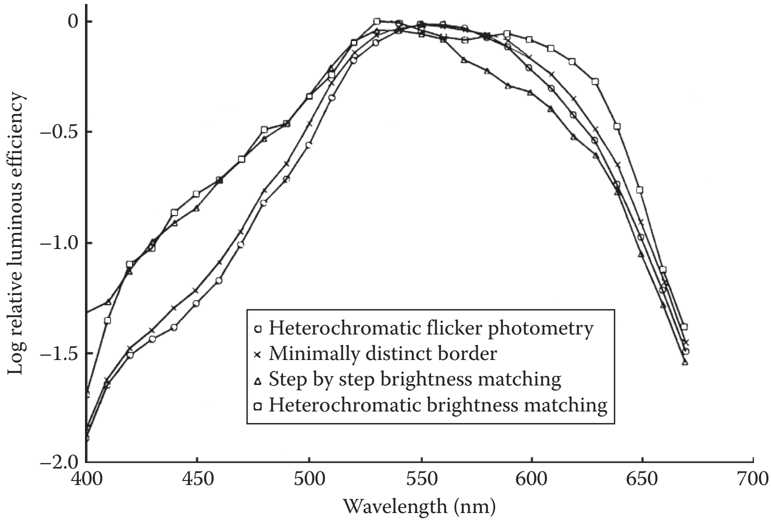

FIGURE 2.14 Log relative luminous efficiency measured by the heterochromatic flicker and the minimally distinct border methods, in which only the achromatic non-opponent channel is active, and by the heterochromatic brightness matching and step-by-step brightness matching methods, in which both the achromatic non-opponent channel and the chromatic opponent channels are active. The relative spectral sensitivity functions measured by the heterochromatic flicker and minimally distinct border methods closely match the CIE modified photopic observer. (After Comerford, J.P. and Kaiser, P.K., *J. Opt. Soc. Am.*, 64, 466, 1975.)

are active and the fovea is blind. As if this pattern of changing spectral sensitivities were not enough, different spectral sensitivities occur within the photopic state, depending on the method used to make the measurements and hence the extent to which the achromatic, non-opponent and chromatic, opponent channels of the human visual system are stimulated (Figure 2.14).

To bring some order to this potential chaos, the CIE has recognized three fixed different spectral sensitivities known as the CIE standard photopic observer, the CIE modified photopic observer and the CIE standard scotopic observer. These relative luminous efficiency functions, shown in Figure 1.2, are used in the fundamental definition of light to convert from radiometric quantities to photometric quantities. As for the mesopic state, despite the complexities discussed by Stockman and Sharpe (2006), the CIE now has a system for predicting the varying spectral sensitivity of the retina outside the fovea when both rods and cones are active (CIE, 2010a). However, because scotopic vision is largely irrelevant to lighting practice and the mesopic spectral sensitivity has only recently been agreed and the CIE modified photopic observer only makes a difference for light sources with a lot of power at short wavelengths, virtually all photometric quantities used in lighting practice are still measured using the CIE standard photopic observer. Consequently, it should not come as a surprise when the visual effects of light sources with different spectral contents are not the same when the two light sources are matched photometrically. The fact is that the CIE standard observers are primarily designed to facilitate the measurement of light rather than to describe the operation of the visual system precisely. The variability of the spectral sensitivity of the human visual system, depending on which photoreceptors are stimulated and which of the vision channels are active, implies that conditions in which the actual spectral sensitivity of the visual system is different from the CIE standard photopic observer are likely to occur quite frequently.

2.3.3 Accommodation

There are three optical components involved in the ability of the eye to focus an image on the retina. The first is the thin film of tears on the cornea. This film is important because it cleans the surface of the eye, starts the optical refraction process necessary for focusing objects and smoothes out small imperfections in the surface of the second optical component, the cornea. The cornea covers the transparent anterior one fifth of the eyeball (Figure 2.4). With the tear layer, it forms the major refracting component of the eye and gives the eye about 70% of its optical power. The crystalline lens provides most of the remaining 30% of the optical power. The ciliary muscles have the ability to change the curvature of the lens and thereby adjust the power of the eye's optical system in response to changing target distances; this change in optical power is called accommodation.

Accommodation is a continuous process, even when fixating, and is always a response to an image of the target located on or near the fovea rather than in the periphery of the retina. It is used to bring a defocused image into focus. It may be changed rapidly, so as to shift focus from one location to another, or gradually, so as to keep a target which is moving in a fore-and-aft direction in focus. Any condition, either physical or physiological, that handicaps the fovea, such as a low light level, will adversely affect accommodative ability. As adaptation luminance decreases below 0.03 cd/m^2, the range of accommodation narrows so that it becomes increasingly difficult to focus objects near and far from the observer (Leibowitz and Owens, 1975). Blurred vision and eyestrain can be consequences of limited accommodative ability. When there is no stimulus for accommodation, as in complete darkness or in a uniform luminance visual field such as in a dense fog, the visual system typically accommodates to focus a target approximately 70 cm away.

2.4 CAPABILITIES OF THE VISUAL SYSTEM

The human visual system, like every other physiological system, has a limited range of capabilities. A convenient way to describe these limits is to set out what are called the thresholds of vision. Qualitatively, a visual threshold is the value of a stimulus to the visual system that can just be seen under a specified condition. A common experience of a threshold measurement occurs during a visit to an optician. To measure the smallest print size that can be read, the patient is shown a series of letters printed at the same luminance contrast but in decreasing sizes. The patient starts with large-sized letters that can be read correctly every time they are presented. As the print size decreases, the letters become more difficult to read, until the patient takes longer to decide on what the letter is and begins to make mistakes, that is, responds with some wrong letters. As the print size continues to decrease, more mistakes are made until the patient is essentially guessing, that is, the percentage of correct responses is at the level of chance. Exactly what percentage of correct responses is taken as representing threshold is a matter of convention, the usual level being 50%, after correction for guessing.

Threshold measurements come in many different forms and depend on many different variables, most of which interact. Threshold measurements provide well-defined and sensitive metrics to explore the operation of the visual system and so have been extensively used in the field of vision science, but for the practice of lighting, threshold measurements are mainly of interest for determining what will not be seen rather than how well something will be seen. Knowing what will not be seen is sometimes useful. For example, for a light source manufacturer, it is useful to know what differences in light source spectrum are allowable before the same nominal light sources will be seen to differ in colour and how much light output fluctuation can be produced before the lamp will be seen to flicker. The intention here is to summarize the thresholds of relevance to the practice of lighting and how they are affected by the characteristics of the human visual system. For these threshold measurements, it can be assumed that the observers were all fully adapted, that the target was presented on a field of uniform luminance and, unless otherwise stated, that the observers' accommodation was correct.

2.4.1 Threshold Measures

The threshold capabilities of the human visual system can conveniently be divided into spatial, temporal and colour classes.

2.4.1.1 Spatial Threshold Measures

Spatial threshold measures relate to the ability to detect a target from its background or to resolve detail within a target. For spatial threshold measures, it is usually assumed that the target does not vary with time. Common spatial threshold measures are threshold luminance contrast and visual acuity.

The luminance contrast of a target quantifies its visibility relative to its immediate background. The higher is the luminance contrast, the easier it is to detect the target. There are three different forms of luminance contrast commonly used for uniform luminance targets seen against a uniform luminance background. There is no agreement on how to measure luminance contrast for complex objects when contrast can occur within the target (Peli, 1990). For uniform targets seen against a uniform background, luminance contrast is defined as

$$C = \frac{L_t - L_b}{L_b}$$

where

C is the luminance contrast

L_b is the luminance of the background

L_t is the luminance of the target

This formula gives luminance contrasts which range from 0 to 1 for targets which have details darker than the background and from 0 to infinity for targets which have details brighter than the background. It is widely used for the former, for example, dark printed text on white paper.

Another form of luminance contrast for a uniform target seen against a uniform background is defined as

$$C = \left(\frac{L_t}{L_b}\right)$$

where C, L_b and L_t are defined in the previous equation.

This formula gives luminance contrasts that can vary from 0, when the target has zero luminance, to infinity, when the background has zero luminance. It is often used for self-luminous displays, for example, computer monitors.

For targets that have a periodic luminance pattern, for example, a grating, the luminance contrast is given by

$$C = \frac{L_{max} - L_{min}}{L_{max} + L_{min}}$$

where

C is the luminance contrast
L_{max} is the maximum luminance
L_{min} is the minimum luminance

This formula gives luminance contrasts that range from 0 to 1, regardless of the relative luminances of the target and background. It is sometimes called the luminance modulation.

Given the different forms of luminance contrast measure, it is always important to understand which is being used.

Visual acuity is a measure of the ability to resolve detail for a target with a fixed luminance contrast. Many different targets can be used in the measurement of visual acuity, from spots, through standard optometric letters and Landolt rings, to gratings. Visual acuity is most meaningfully quantified as the angle subtended at the eye by the detail that can be resolved on 50% of the occasions the target is presented. This angle is usually expressed in minutes of arc, although sometimes the reciprocal is used. Using this measure, the visual acuity corresponding to normal vision is taken to be 1 min arc.

Unfortunately for simplicity, there are a number of other measures used to quantify visual acuity. A relative measure is commonly used by the medical profession. Visual acuity is measured in a doctor's surgery with a chart consisting of high luminance contrast letters arranged in rows of decreasing size. This chart is viewed from a distance at which the eye is accommodated close to infinity, typically 6 m, and the patient is asked to read out the letters in order of size until the different letters can no longer be discriminated. The measure used is called Snellen visual acuity and is the ratio of the viewing distance to the distance at which the detail in the last letter to be discriminated subtends 1 min arc. Snellen visual acuity is usually expressed as ratio, such as 6/12, which means that the patient can only read a given letter at 6 m that an average member of the population with normal vision can read from 12 m. Other ways in which this ratio can be expressed are as a decimal (6/12 = 2.0) or as the minimum angle of resolution (MAR), that is, the angle subtended by the detail in the last letter to be discriminated when viewed from 6 m. This means a Snellen visual acuity of 6/12 represents a MAR of 2 min arc. Further, for a grating, visual acuity is sometimes expressed as spatial frequency, measured in cycles per degree. This is the number of cycles of the grating that subtends 1° from the observer's viewing position when the grating can be identified as a grating on 50% of the occasions it is presented.

Again, given the different forms of visual acuity that are used by different professions, it is important to be sure which metric is being used.

2.4.1.2 Temporal Threshold Measures

Temporal threshold measures relate to the speed of the response of the human visual system and its ability to detect fluctuations in luminance. For temporal threshold measures, it is usually assumed that the target is fixed in position.

The ability of the human visual system to detect fluctuations in luminance can be measured as the frequency of the fluctuation, in Hertz, and the amplitude of the fluctuation, for the stimulus that can be detected on 50% of the occasions it is presented. The amplitude is expressed as

$$M = \frac{L_{max} - L_{min}}{L_{max} + L_{min}}$$

where

M is the modulation
L_{max} is the maximum luminance
L_{min} is the minimum luminance

This formula gives modulations that range from 0 to 1. Sometimes, modulation is expressed as a percentage modulation, calculated by multiplying the modulation by 100.

2.4.1.3 Colour Threshold Measures

Colour threshold measures are based on the separation in colour space of two colours that can just be discriminated. In principle, the separation can be measured in any of the colour spaces described in Chapter 1, but by far, the most widely used has been the CIE 1931 chromaticity diagram and the related CIE 1976 UCS diagram.

2.4.2 Factors Determining Visual Threshold

There are three distinct groups of factors that influence the measured threshold, using any of the aforementioned metrics. These groups are visual system factors, target characteristics and the background against which the target appears.

Important visual system factors are the luminance to which the visual system is adapted, the position in the visual field where the target appears and the extent to which the eye is correctly accommodated. The luminance to which the visual system is adapted determines which visual photoreceptor types are operating. The position in the visual field in which the target appears determines the size of the receptive field available to the visual system, the type of visual photoreceptors available and the spectral sensitivity. The state of accommodation determines the retinal image quality. As a general rule, the lower the luminance to which the visual system is adapted, the further the target is from the fovea, and the more mismatched the accommodation of the eye is to the viewing distance, the larger will be the threshold values.

Important target characteristics are the size and luminance contrast of the target and the colour difference between the target and the immediate background. Any one of these three task characteristics can be the threshold measure of interest but the others will interact with it. This means that the visual acuity of a target will be different for targets of different luminance contrast and colour difference. As a general rule, the closer the other target characteristics are to their own threshold, the greater will be the threshold of the measured variable. For example, the visual acuity for a low luminance contrast, achromatic target will be much larger than for a high luminance contrast, achromatic target.

As for the effect of the background against which the target appears, the important factors are the area, luminance and colour of the background. These factors are important because they determine the luminance and colour adaptation state of the visual system and the potential for interacting with the image processing of the target. As a general rule, the larger the area around the target that is of a similar luminance to the target and neutral in colour, the smaller will be the threshold measure.

2.4.3 Spatial Thresholds

About the simplest possible visual task is the detection of a spot of light presented continuously against a uniform luminance background. For such a target, the visual system demonstrates spatial summation, that is, the product of target luminance and target area is a constant. This relationship between target luminance and target area is known as Ricco's law. It implies that the total amount of energy required to stimulate the visual system so that the target can be detected is the same, regardless of whether it is concentrated in a small spot or distributed over a larger area. Spatial summation breaks down when the target is above a given size, called the critical size. The critical size varies with the angular deviation from the fovea. The critical size is about 0.5° at 5° from the fovea and about 2° at 35° from the fovea (Hallet, 1963). There is very little spatial summation in the fovea, the critical size being about 6 min arc.

Given that the size of the target is above the critical size, the detection of the presence of a spot of light is determined simply by the luminance contrast. For the luminance of the surround greater than about 1–10 cd/m^2, that is, in the photopic range, there is a constant relationship between the luminance difference of the target and the background luminance known as Weber's law. This relationship takes the form

$$\frac{L_t - L_b}{L_b} = k$$

where
L_t is the luminance of the target
L_b is the luminance of the background
k is a constant

A more general picture of the effect of adaptation luminance on threshold contrast for targets of different size is shown in Figure 2.15. The increase in threshold contrast as adaptation luminance decreases is obvious, as is the increase in threshold contrast with decreasing target size (Blackwell, 1959).

Figure 2.16 shows the threshold contrast measured for circular targets of different sizes, occurring at different eccentricities from the fovea (Blackwell and Moldauer, 1958). It can be seen that the threshold luminance contrast is a minimum at the fovea and it increases as eccentricity from the fovea increases. Also apparent is the interaction between the size of the disc and the eccentricity of its locations. Specifically, higher threshold luminance contrasts are associated with smaller target sizes, and the increase in threshold luminance contrast with increasing eccentricity is greater the smaller the size of the disc. Another interaction with

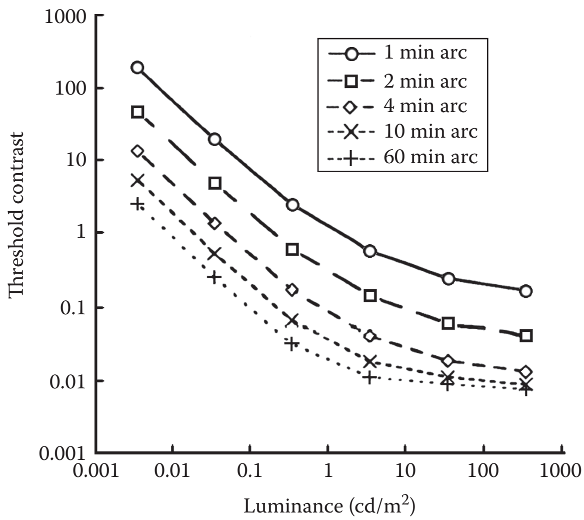

FIGURE 2.15 Threshold contrast plotted against background luminance for disc targets of various diameters, viewed foveally. The discs were presented for 1 s. (After Blackwell, H.R., *Illum. Eng.*, 54, 317, 1959.)

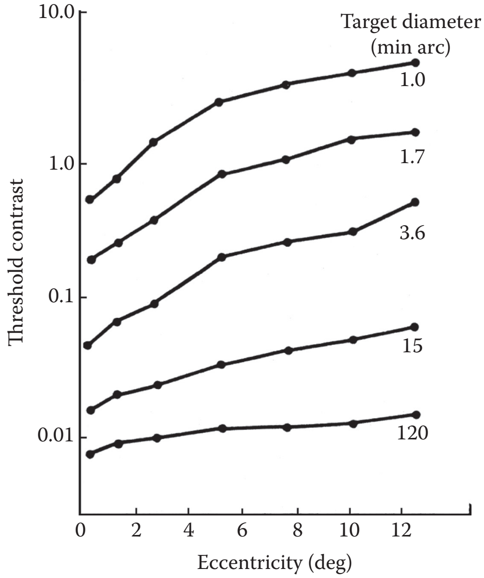

FIGURE 2.16 Threshold contrast for disc targets of various diameters, presented for 330 ms, at various degrees of eccentricity, at a background luminance of 257 cd/m^2. (After Blackwell, H.R. and Moldauer, A.B., *Detection Thresholds for Point Sources in the Near Periphery*, EPRI Project 2455, Engineering Research Institute, University of Michigan, Ann Arbor, MI, 1958.)

size occurs with the extent to which the target is focused on the retina. For discs less than 40 s arc in diameter, threshold contrast is rapidly reduced by blur, but for discs greater than 20 min arc in diameter, there is no effect of blur on the detection of presence (Ogle, 1961).

Threshold luminance contrast is relevant to the detection of targets on a background. Targets with a luminance contrast close to or below the threshold value are unlikely to be seen, and targets with a luminance contrast more than twice the threshold value are likely to be seen every time, provided the conditions are similar to those in which the threshold measurements were made.

Turning now to visual acuity, Figure 2.17 shows the variation in visual acuity with adaptation luminance for foveal viewing of the target. As adaptation luminance increases, visual acuity, measured as the reciprocal of the minimum gap size, increases, approaching an asymptote at very high luminances corresponding to about 0.45 min arc (Shlaer, 1937).

Figure 2.18 shows the variation in visual acuity, measured as minimum gap size, with eccentricity from the fovea. These results show the expected deterioration in visual acuity with increasing eccentricity, the rate of deterioration being enhanced beyond about 30° eccentricity (Mandlebaum and Sloan, 1947).

Of course, these results are for photopic conditions. In mesopic and scotopic conditions, the variation of visual acuity with eccentricity is different. Figure 2.19 shows visual acuity, measured as the reciprocal of the minimum gap size, plotted against eccentricity, for a range of adaptation luminances. For the adaptation luminance of

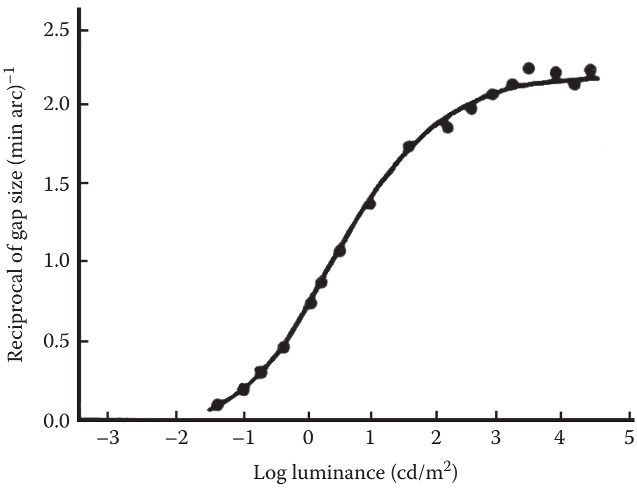

FIGURE 2.17 Visual acuity, expressed as the reciprocal of the minimum gap size, for a Landolt ring, plotted against log background luminance. (After Shlaer, S., *J. Gen. Physiol.*, 21, 165, 1937.)

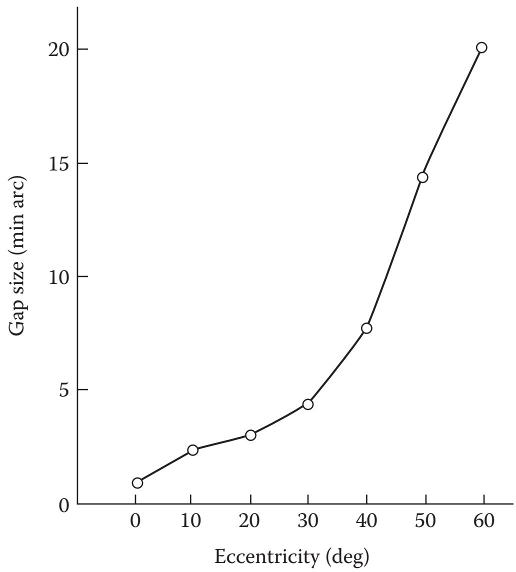

FIGURE 2.18 Visual acuity, expressed as the minimum gap size, for a Landolt ring target presented at different degrees of eccentricity. The target was presented for 220 ms on a background luminance of 245 cd/m^2. (After Mandlebaum, J. and Sloan, L.L., *Am. J. Ophthalmol.*, 30, 581, 1947.)

3.2 cd/m^2, that is, around the mesopic/photopic boundary, acuity is at about 1 min arc in the fovea and declines rapidly to about 10 min arc as eccentricity increases. For adaptation luminances below 0.006 cd/m^2, that is, approaching the scotopic state where the fovea is blind and only the rod photoreceptors are active, visual acuity is best at about 10 min arc, 4°–8° off-axis (Mandlebaum and Sloan, 1947).

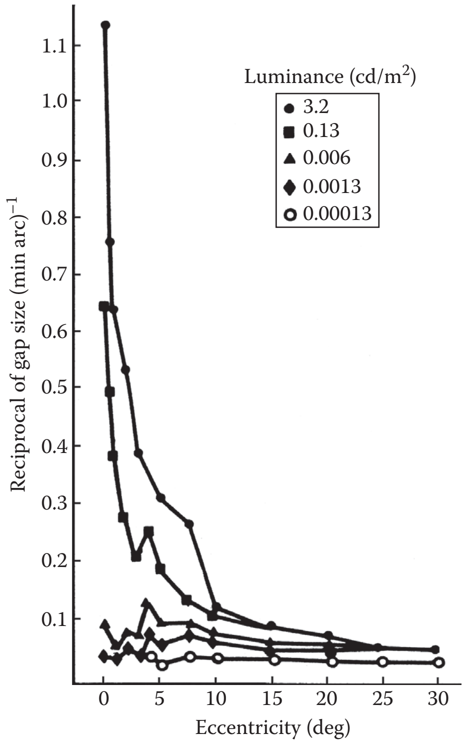

FIGURE 2.19 Visual acuity, expressed as the reciprocal of minimum gap size, for a Landolt ring target presented at different degrees of eccentricity, over a range of background luminances. (After Mandlebaum, J. and Sloan, L.L., *Am. J. Ophthalmol.*, 30, 581, 1947.)

Figure 2.20 shows the effect of the luminance of the background on visual acuity, measured as the reciprocal minimum gap size (Lythgoe, 1932). Visual acuity is measured using a Landolt ring, seen against a small rectangular background which is itself surrounded by a much larger area. When the luminances of the immediate background and the extensive surround are the same, visual acuity continues to improve monotonically as background luminance increases. When the luminance of the surround is very low relative to that of the immediate background, there is an optimum background luminance for visual acuity, above which visual acuity declines.

In the above discussion, threshold contrast and visual acuity have been considered separately, because threshold contrast is usually measured with large size targets, without detail, and visual acuity is measured with high luminance contrast targets, with detail. But many things of practical interest vary in both luminance contrast and size of detail, and these two target characteristics can be expected to interact. The threshold capabilities of the visual system to such targets can be expressed as the contrast sensitivity function. This is a rather grand name for what is essentially a simple piece of information, the frequency response of the visual system to spatial variations in luminance. The contrast sensitivity function of the visual system is measured using sine wave grating targets of different

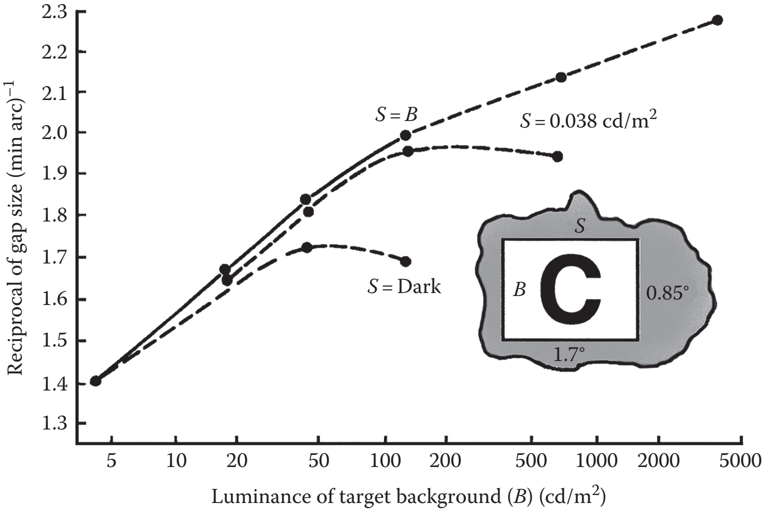

FIGURE 2.20 Visual acuity, expressed as the reciprocal of minimum gap size for a Landolt ring, plotted against background luminance, for different levels of surround luminance. The background luminance (*B*) is the luminance of a rectangular area subtending 1.7° by 0.85° with the Landolt ring at its centre. The surround luminance (*S*) is the luminance of the area surrounding the background rectangle. (After Lythgoe, R.J., *The Measure of Visual Acuity*, MRC Special Report No. 173, His Majesty's Stationary Office, London, U.K., 1932; Illuminating Engineering Society of North America (IESNA), *The Lighting Handbook*, 9th edn., IESNA, New York, 2000a.)

spatial frequencies and adjustable modulation. The spatial frequency of the grating consists of the number of cycles of the grating that lie within a 1°-wide field of view for the observer and hence is expressed in cycles per degree. The threshold contrast condition is usually measured as modulation, but it is often displayed as contrast sensitivity which is the reciprocal of modulation. Figure 2.21 shows the contrast sensitivity functions for different adaptation luminances (van Nes and Bouman, 1967).

The value of this apparently esoteric piece of information is that any variation in luminance across a surface can be represented as a waveform, and any waveform can be represented as a series of sine waves of different amplitudes and frequencies. The response of the visual system to sine waves of different amplitudes and frequencies is given by the contrast sensitivity function. Thus, the contrast sensitivity function can be used to determine if a complex variation in luminance will be seen. If the luminance pattern has contrast sensitivities at all spatial frequencies that are greater than the threshold contrast sensitivities, the luminance pattern will be invisible. It is only when at least one spatial frequency has a contrast sensitivity below the threshold contrast sensitivity that the luminance pattern will be visible. The extent to which the luminance pattern will be seen in its entirety depends on the number of spatial frequencies for which the contrast sensitivity lies below the threshold contrast sensitivity; the more spatial frequencies for which this occurs, the more complete is the perception of the luminance pattern. Contrast sensitivity functions

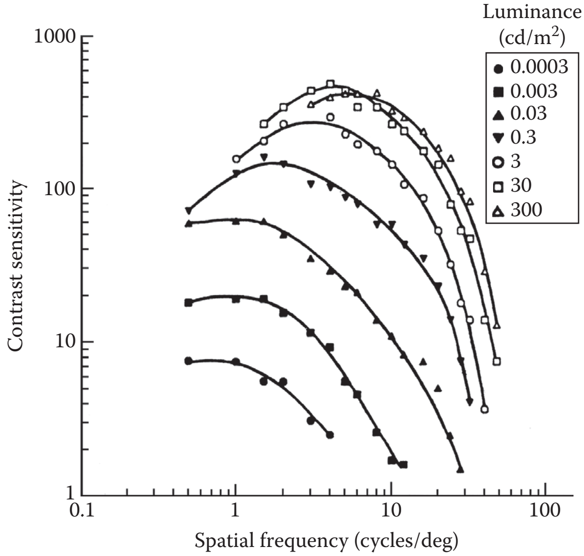

FIGURE 2.21 Contrast sensitivity functions for sine wave gratings at different levels of background luminance, covering the photopic, mesopic and scotopic states of the visual system. (After van Nes, F.L. and Bouman, M.A., *J. Opt. Soc. Am.*, 47, 401, 1967.)

can be used for many practical purposes. For example, they can be used to determine if the luminance variation of a wall-washing installation will be noticed from a given distance and what size a road sign needs to be read from a given distance. The distance from which the observer views the luminance pattern is important because changing the viewing distance changes the spatial frequency of the pattern. As viewing distance increases, the spatial frequency of a fixed grating increases.

Returning now to Figure 2.21, it is apparent that increasing adaptation luminance increases both the contrast sensitivity and the maximum spatial frequency detectable, that is, it produces a lower threshold contrast and a finer visual acuity. Also clear is the fact that the change in contrast sensitivity function is slight for high luminances, but it changes rapidly below adaptation luminance of about 30 cd/m^2. The deterioration takes the form of reduced contrast sensitivities at all spatial frequencies and a decrease in the spatial frequency at which maximum contrast sensitivity occurs. Another interesting feature of the contrast sensitivity function is the fact that it shows a maximum in contrast sensitivity. Both very high and very low spatial frequencies show reduced contrast sensitivity and so are less likely to be seen than are intermediate spatial frequencies.

The effect of eccentricity on the contrast sensitivity function is shown in Figure 2.22. As might be expected from the increase in receptive field size with increasing eccentricity, the contrast sensitivity function shows a dramatic reduction in the highest spatial frequency visible as deviation from the fovea increases, as well as a reduction in peak contrast sensitivity. What this means is that it is not possible to see fine detail more than a few degrees away from the fovea.

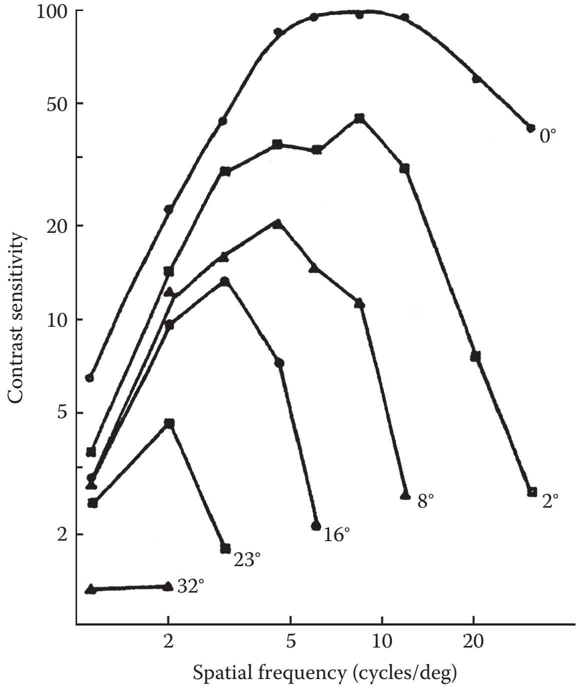

FIGURE 2.22 Contrast sensitivity functions for a 2.5° stimulus presented at different degrees of eccentricity. (After Hilz, R. and Cavonius, C.R., *Vision Res.*, 14, 1333, 1974.)

As for the effect of incorrect accommodation, Campbell and Green (1965) showed that the effect of defocus is large at high spatial frequencies but limited at low spatial frequencies.

2.4.4 Temporal Thresholds

The simplest possible form of temporal visual task is the detection of a spot of light briefly presented against a uniform luminance background, that is, a flash of light. For such a target, the visual system demonstrates temporal summation, that is, the product of target luminance and the duration of the flash is a constant. This relationship between target luminance and duration is known as Bloch's law. It implies that the total amount of energy required to stimulate the visual system so that the target can be detected is the same, regardless of the time for which the target is presented. Temporal summation breaks down above a fixed duration, called the critical duration. The critical duration varies with adaptation luminance, ranging from 0.1 s for scotopic luminances to 0.03 s for photopic luminances. For presentation times longer than the critical duration, presentation time has no effect, the ability to detect the flash being determined by the difference in luminance between the flash and the background. When there are multiple flashes, additional factors, such as the time interval between flashes, become important (Holmes, 1971).

While the ability to detect a flash or flashes is of interest for signalling purposes (Bullough et al., 2013), an aspect of temporal thresholds of wider relevance to lighting is the ability to detect flicker. All light sources operating from an AC electrical supply produce some fluctuation in light output, the waveform depending on the physical properties of the light source and the characteristics of the electrical supply to the light source. A light source is said to be flickering when the fluctuation in light output is visible. Figure 2.23 shows the maximum frequency of a sine wave fluctuation at 100% modulation that is visible at different retinal illuminations, for visual fields of different sizes (Hecht and Smith, 1936). This maximum frequency is called the critical fusion frequency (CFF). It is apparent from Figure 2.23 that the CFF increases with increasing retinal illumination and with area, although the increase is not a simple linear function. Rather, for large field sizes, such as might occur when using indirect lighting, the CFF increases linearly with retinal illumination in the scotopic state, shows little change in the mesopic state and increases linearly in the photopic state until saturation occurs.

While the CFF is a useful metric of flicker detection, it only tells part of the story. Its limitation is that it is based on a stimulus with 100% modulation. Figure 2.24 shows a more general way of treating the temporal characteristics of the visual system – the temporal modulation transfer function (Kelly, 1961). The left panel of Figure 2.24 shows the percentage modulation amplitude, plotted against frequency of the oscillation at different levels of retinal illumination measured in trolands (see Section 4.2). These data were collected from a 60°-diameter field, uniformly illuminated, the flicker waveform being sinusoidal. This panel shows that increasing the retinal illumination increases the sensitivity to modulation and shifts the frequency for peak sensitivity from about 5 to 20 Hz. The other important point is that apart from the lowest retinal illuminance, the results for all the other retinal illuminances come to a common curve at low frequencies but have different curves

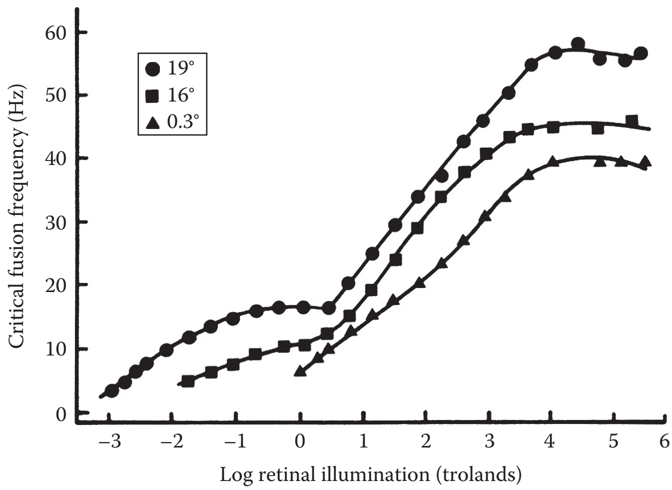

FIGURE 2.23 CFF plotted against log retinal illumination, for three different test field sizes. (After Hecht, S. and Smith, E.L., *J. Gen. Physiol.*, 19, 979, 1936.)

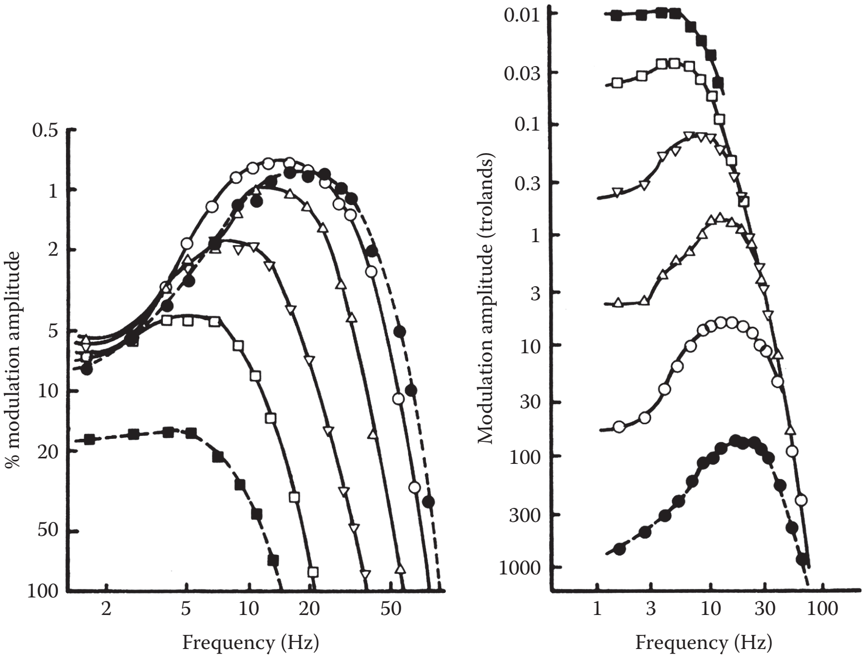

FIGURE 2.24 Temporal modulation transfer functions for a large visual field at different retinal illuminations. The modulation is expressed as percentage modulation in the left diagram and absolute modulation in the right diagram. The retinal illuminations are as follows: ●, 9300 trolands; ○, 850 trolands; △, 77 trolands; ▽, 7.1 trolands; □, 0.65 trolands; ■, 0.06 trolands. (After Kelly, D.H., *J. Opt. Soc. Am.*, 51, 422, 1961.)

at high frequencies. This implies that at low frequencies, the ability to detect flicker is determined by the percentage modulation but at high frequencies it is not. The right panel of Figure 2.24 shows the same data, but now the vertical axis is plotted against the absolute modulation amplitude of the retinal illumination. The shift in frequency for peak sensitivity with increasing retinal illumination is again apparent, but now the high-frequency end of the response for different retinal illuminations forms a common envelope. This means that the high-frequency response of the visual system is consistently related to the absolute modulation of the fluctuation, not the percentage modulation. Flicker in lighting installations usually involves high frequencies.

Figure 2.24 can be used to determine if a light fluctuation will be visible for a large area fluctuation. For a sine wave oscillation, if the modulation at the given frequency is above the curve for the appropriate retinal illuminance, the flicker will not be visible. If it is below the curve, it will be visible. But what can be done if the waveform is not sinusoidal? The left panel of Figure 2.24 is the temporal equivalent of the contrast sensitivity function and can be used in an analogous way. To predict whether a given fluctuation waveform will be visible, the waveform should be represented by a Fourier series of different frequencies and amplitudes. If the modulations of all the components of the series lie above the appropriate temporal modulation transfer function curve, then the fluctuation will not be visible. If any of the components are below the curve, the fluctuation will be visible in some form. While these statements are true in principle, it should always be remembered that there are considerable individual differences between people in their sensitivity to flicker, so to be sure that a flicker will not be seen, it is a good idea to use waveforms that have amplitudes and frequencies well clear of the threshold region represented by the temporal modulation transfer function.

2.4.5 Colour Thresholds

Both the spatial and temporal thresholds discussed earlier have been measured using achromatic targets lit by nominally white light, but in the photopic state, the human visual system has a well-developed ability to discriminate colours. Figure 2.25 shows what are called the MacAdam ellipses, ten times enlarged, plotted in the CIE 1931 chromaticity diagram (MacAdam, 1942). Each ellipse represents the standard deviation in the chromaticity coordinates for colour matches made between two, small visual fields with the reference field having the chromaticity of the centre point of

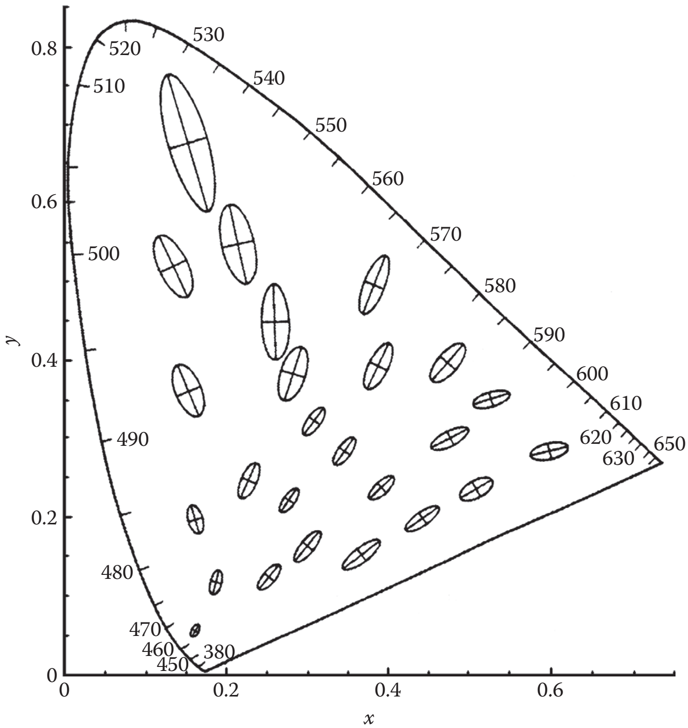

FIGURE 2.25 The CIE 1931 chromaticity diagram with the MacAdam ellipses displayed, multiplied 10 times. (After MacAdam, D.L., *J. Opt. Soc. Am.*, 32, 247, 1942; Wyszecki, G. and Stiles, W.S., *Color Science: Concepts and Methods, Quantitative Data and Formulas*, John Wiley & Sons, New York, 1982.)

the ellipse. The lighting industry uses three- to seven-step MacAdam ellipses as tolerance limits for quality control in the manufacture of different light sources. Given that a three-step MacAdam ellipse represents three standard deviations and that three standard deviations should include the colour matches made by more than 99% of the population, it may seem that such tolerances are too lax. In practice, it has not been a problem, probably because the MacAdam ellipses were obtained in conditions ideal for comparison (simultaneous viewing of adjacent small fields by a highly practiced observer). Colour discrimination between targets presented successively or between targets in which there are a wide range of colours and patterns present is more difficult (Narendran et al., 2000). While light sources are not often seen in conditions ideal for colour comparisons, there is still a need to be careful. For light-emitting diodes, seven-step MacAdam ellipses are widely used for quality control, and production is commonly sorted into bins with similar colour characteristics prior to sale so as to reduce the risk that what are nominally the same lamps will be seen to differ in colour.

Figure 2.25 is for people with normal colour vision. People with defective colour vision are unable to make such fine discriminations in colour. Figure 2.26 shows what are called isochromatic lines on the CIE 1931 chromaticity diagram for the three types of dichromat. All colours along a line will appear the same in hue and saturation to the dichromat, although they may vary in brightness or lightness. The directions of the lines in Figure 2.26 demonstrate that protanopes and deuteranopes will have similar problems in discriminating among reds and greens, but deuteranopes will find discriminating among purples much easier than will protanopes. As for tritanopes, these will have little difficulty discriminating among reds and greens but will have a problem discriminating between blues.

2.4.6 Interactions

The information given above represents a minute portion of the data available on visual thresholds for different conditions. Further, it is based on a restricted range of variables. The spatial thresholds all use an achromatic target seen on a field of uniform luminance. The temporal thresholds use fluctuations in luminance without a change in colour. The colour thresholds use side-by-side comparisons between small uniform visual fields with the same luminance. Nonetheless, the data given are enough to demonstrate the effects of the major factors: adaptation luminance, position in the visual field and state of accommodation. Other factors, such as movement of the target, interact with these major factors to determine threshold values. Figure 2.27 shows the effect of movement on the threshold contrast of a 5° bar pattern target stationary or moving at 24°/s at different eccentricities on a background luminance of 9.8 cd/m^2 (Rogers, 1972). There is only a small difference in threshold contrast between stationary and moving targets in the fovea, but the difference increases dramatically with increasing eccentricity, the stationary target having ever higher threshold contrasts but the moving target hardly changing.

Figure 2.28 shows the visual acuity for smooth relative movement of target and observer at different velocities (Miller and Ludvigh, 1962). There is a slow

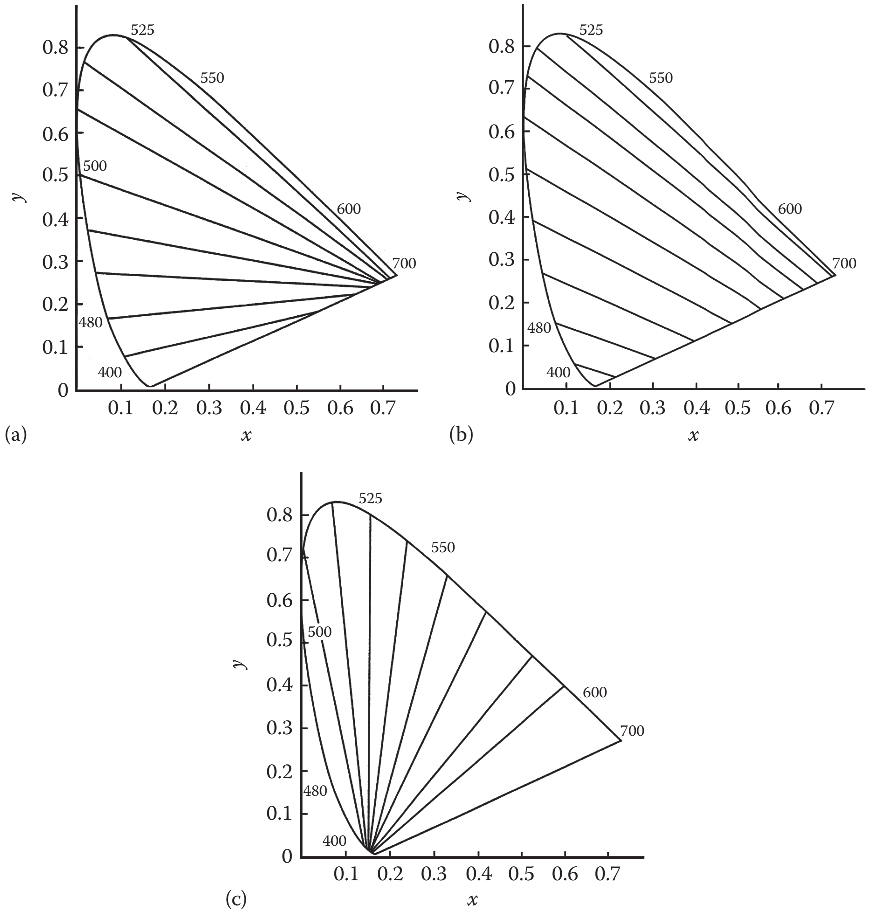

FIGURE 2.26 Isochromatic lines for (a) protanopes, (b) deuteranopes and (c) tritanopes. Surfaces represented by chomaticities at any point along a line will look the same colour to a person with the given form of defective colour vision, although they may differ in brightness or lightness.

deterioration in visual acuity with increasing velocity up to about 40°/s, but at higher velocities, visual acuity deteriorates rapidly. This result is understandable if it is assumed that for velocities below 40°/s, it is possible to use smooth pursuit eye movements to keep the target close to the fovea. Of course, this will not be possible if the target is moving in an unexpected manner, involving sudden changes of course and velocity.

There are many other factors that interact to determine a specific threshold condition. One such factor is gender, males having significantly greater sensitivity to fine detail and rapidly moving stimuli than females (Abramov et al., 2012), although the latter are less likely to have defective colour vision. Further, there are large differences between individuals of both genders in threshold measures. Figure 2.29

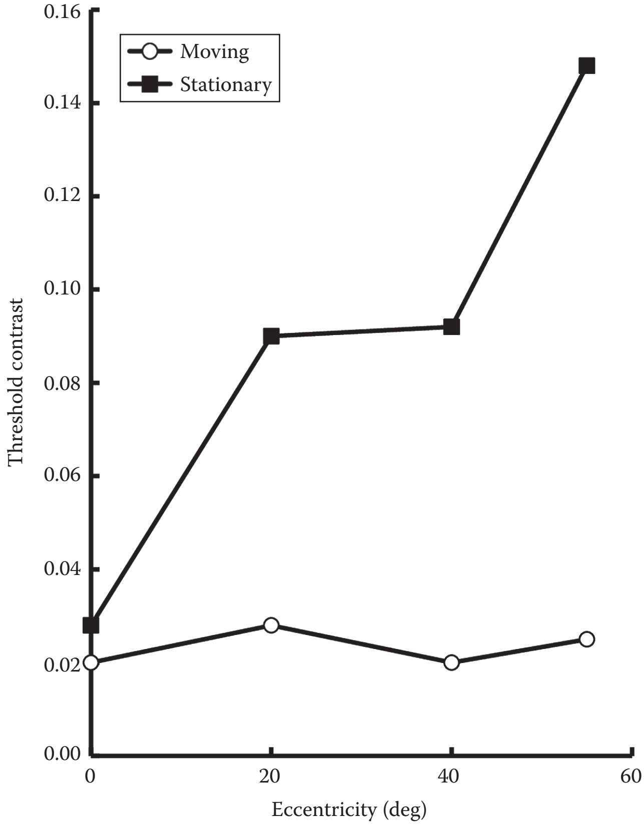

FIGURE 2.27 Threshold contrast plotted against eccentricity for stationary and moving bar pattern targets. (After Rogers, J.G., *Hum. Factors*, 14, 199, 1972.)

shows the threshold contrast measurements for people of different ages at three different adaptation luminances. The trend in threshold luminance contrast with increasing adaptation luminance is obvious as is the general trend of increasing threshold contrast with increasing age. However, what is really impressive are the large differences in threshold contrast between individuals, different enough to ensure that there is some overlap in threshold contrast between the people of 20 and 60 years of age (Blackwell and Blackwell, 1971). Really, if you want to know how a specific combination of factors will affect a specific threshold measure for a specific population, there is little alternative other than to make a direct measurement. However, if all you want is to ensure that a target presented will be clearly visible or definitely invisible, that is, you want your target to be definitely above or below the relevant threshold, then you may be able to use the data derived from the simplified conditions given earlier. Details of many different threshold measurements in a wide range of conditions can be found in Wyszecki and Stiles (1982) and Boff and Lincoln (1988).

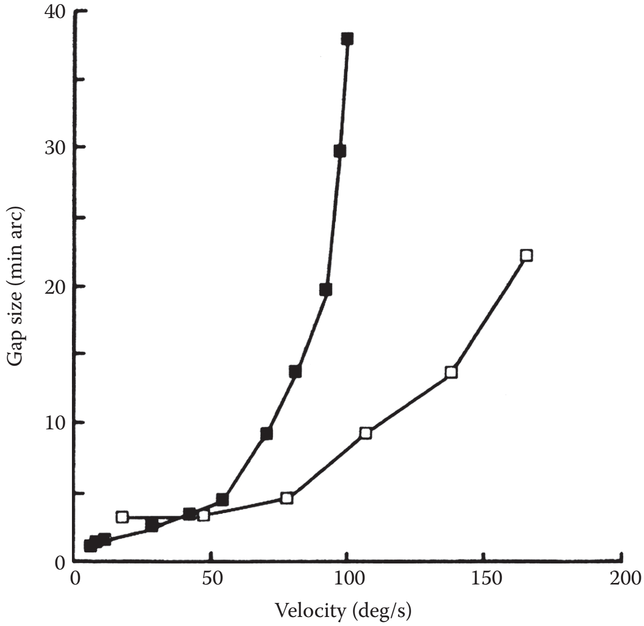

FIGURE 2.28 Visual acuity for Landolt rings, expressed as gap size in minutes of arc, for different angular velocities. The filled symbols are for the target moving. The open symbols are for the observer moving. (After Miller, J.W. and Ludvigh, E., *Surv. Ophthalmol.*, 7, 83, 1962.)

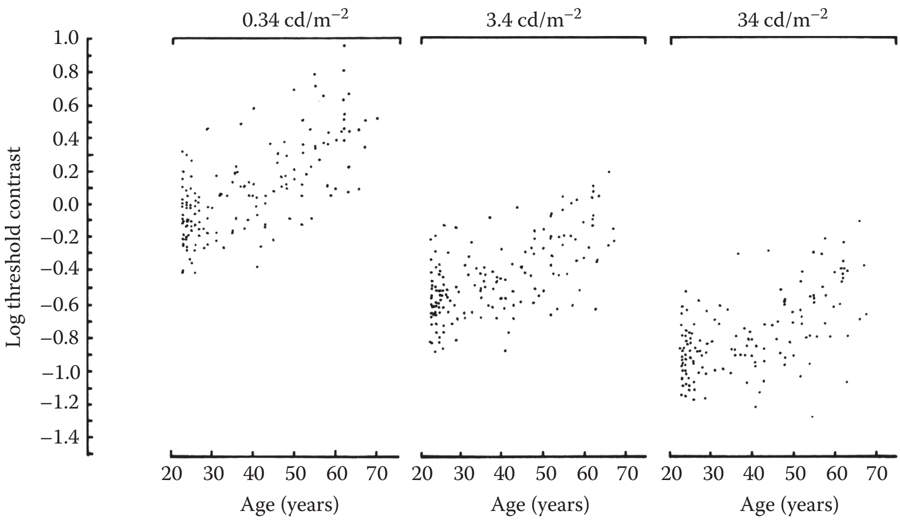

FIGURE 2.29 Log threshold contrasts for individuals of different ages at three different background luminances. (After Blackwell, H.R. and Blackwell, O.M., *J. Illum. Eng. Soc.*, 1, 3, 1971.)

2.5 PERCEPTION THROUGH THE VISUAL SYSTEM

While thresholds define the limits of the capabilities of the human visual system, most of our life is spent looking at things that are well above threshold and hence clearly visible. The topic here is how we perceive these myriad stimuli. The perception of the visual world is not solely determined by the physical stimuli presented to the visual system as the retinal image nor by the characteristics of the visual system described earlier. Rather, the stimuli to the visual system are broken into different elements in the retina; different elements are then transmitted up the different visual channels to the visual cortex where the real world is reassembled guided by past experience and coincident information from other senses (Purves and Beau-Lotto, 2003). As an example of the power of past experience, Figure 2.30 shows a surface with dents and dings in it. If this page is inverted, the dents become dings and vice versa, because previous experience tells us that the light which is casting the shadows usually comes from above. Clearly, there is a gap between our understanding of the visual system and its eventual output, perception of the visual world. The existence of this gap can be understood by an analogy. Consider the output of an orchestra. It consists of rhythm, melody and tonality arranged in complex and subtle patterns that can, when the patterns match our cultural expectations, generate a pleasant emotional response. However, our knowledge of how this is achieved is limited to how each instrument

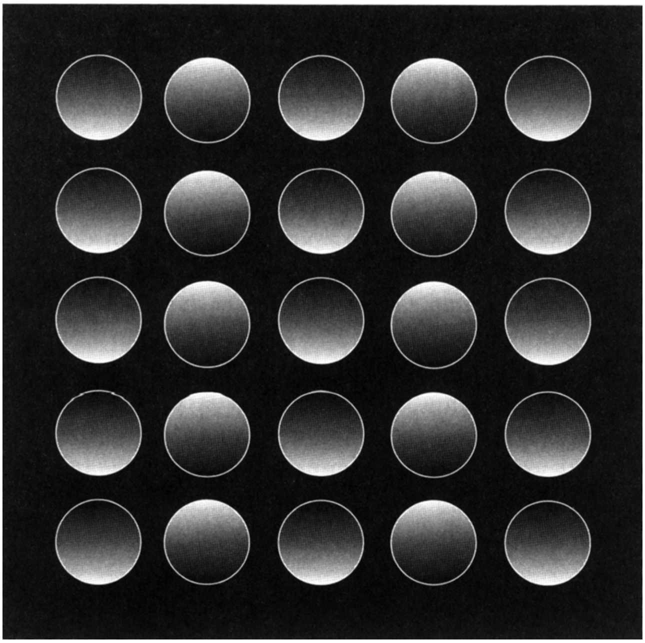

FIGURE 2.30 A surface with circular dents and dings. The distribution of light within each circular area determines whether it is seen as a dent or a ding. (After Illuminating Engineering Society of North America (IESNA), *The Lighting Handbook*, 9th edn., IESNA, New York, 2000a.)

generates sound. In the world of vision, we have some idea of how each instrument behaves but not how they all fit together and how they interact with other information to generate the whole, the perception of the visual world.

When considering how we perceive the world, the overwhelming impression is one of stability in the face of continuous variation. As the eyes move in the head and the head itself moves about, the retinal images of objects move across the retina and change their shape and size according to the laws of physical optics. Further, throughout the day, the spectral content and distribution of daylight changes as the sun moves across the sky and the meteorological conditions vary. Despite these variations, our perception of objects rarely changes. This invariance of perception is called perceptual constancy. The evolutionary advantage in being able to recognize a tiger as a tiger over a wide range of lighting conditions is obvious.

2.5.1 Perceptual Constancies

There are four fundamental attributes of an object that are maintained constant over a wide range of lighting conditions. They are described as follows:

Lightness: Lightness is the perceptual attribute related to the physical quantity, reflectance. In most lighting situations, it is possible to distinguish between the illuminance on a surface and its reflectance, that is, to perceive the difference between a low-reflectance surface receiving a high illuminance and a high-reflectance surface receiving a low illuminance, even when both surfaces have the same luminance. It is this ability to perceptually separate the luminance of the retinal image into its components of illuminance and reflectance which ensures that a piece of coal placed near a window is always seen as black while a piece of paper far from the window is always seen as white, even when the luminance of the coal is higher than the luminance of the paper. This ability to separate illuminance from reflectance under most lighting conditions makes the use of luminance as the basis of lighting design criteria problematical (Jay, 1967, 1971).

Colour: Physically, the stimulus a surface presents to the visual system depends on the spectral content of the light illuminating the surface and the spectral reflectance of the surface. However, quite large changes in the spectral content of the illuminant can be made without causing any changes in the perceived colour of the surface, that is, colour constancy occurs. Colour constancy is similar in many ways to lightness constancy. There are two factors that need to be separated: the spectral distribution of the incident light and the spectral reflectance of the surface. As long as the spectral content of the incident light can be identified, the spectral reflectance of the surface, and hence its colour, will be stable.

Size: As an object gets further away, the size of its retinal image gets smaller, but the object itself is not seen as getting smaller. This is because by using clues such as texture and masking, it is usually possible to estimate the distance and then to compensate unconsciously for the increase in distance. Figure 2.31 shows an illustration of a room, called the Ames room after the inventor, where the cues to distance have been deliberately designed to be misleading when viewed from a specific position. The distortion in perceived size of the people standing in the two corners of the room is apparent.

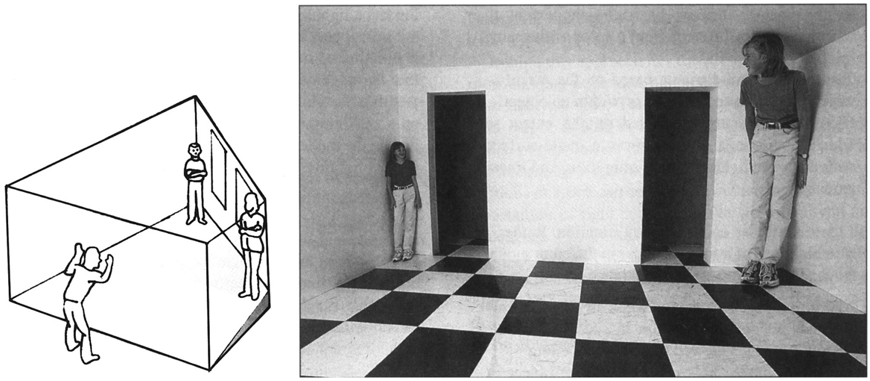

FIGURE 2.31 The Ames room: a demonstration that providing misleading clues to distance will break size constancy. (After Illuminating Engineering Society of North America (IESNA), *The Lighting Handbook*, 9th edn., IESNA, New York, 2000a.)

Shape: As an object changes its orientation in space, its retinal image changes. Nonetheless, in most lighting conditions, the distribution of light and shade across the object makes it possible to determine its orientation in space. This means that in most lighting conditions, a circular plate that is tilted will continue to be seen as a tilted circular plate even though its retinal image is elliptical.

These constancies represent the application of everyday experience and the integration of all the information about the lighting available in the whole retinal image to the interpretation of a part of the retinal image which bears several alternative interpretations. Given this process, it should not be too surprising that the constancies can be broken by restricting the information available coincident with the object being viewed. For example, viewing a uniform luminance surface through an aperture that restricts the view to a limited part of the surface will often eliminate lightness constancy, that is, make it impossible to accurately judge the reflectance. Likewise, eliminating cues to distance, such as gradients in texture, motion parallax and overlapping of objects, will destroy size constancy; changing cues to the plane in which an object is lying will reduce shape constancy; and eliminating information on the spectral content of the illuminant will reduce colour constancy. In general, constancy is likely to break down whenever there is insufficient or misleading information available from the surrounding parts of the visual field. The constancies are most likely to be maintained when there is enough light for the observer to see the object and the surfaces around it clearly, the light being provided by an obvious but not necessarily visible light source. It is also desirable that the light source has a spectral power distribution that covers the entire visible spectrum and is delivered without disability glare. In addition, the constancies are most likely to be maintained when there are a variety of surface colours, including some small white surfaces and there are no large glossy areas, both factors that help with the identification of the spectral content of the light source (Lynes, 1971). Lighting conditions used in display lighting sometimes set out to break the constancies, particularly lightness constancy, in order to give the display some drama.

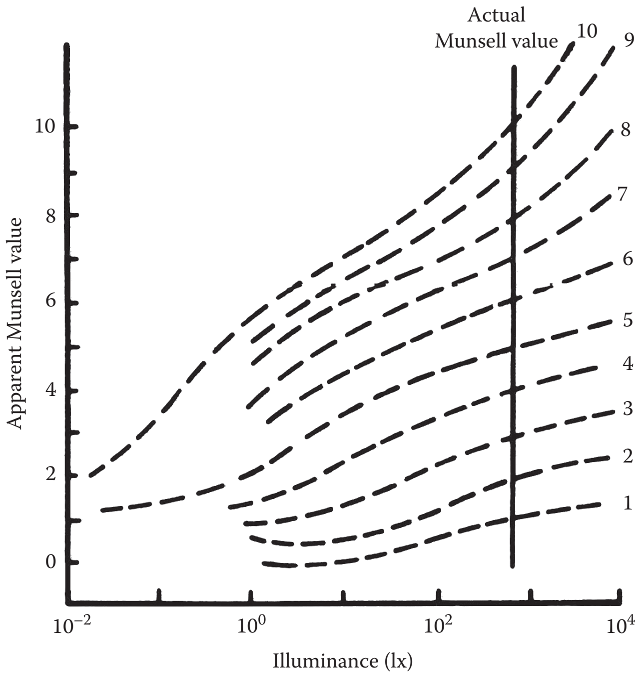

FIGURE 2.32 Apparent Munsell values at different illuminances for surfaces seen against a background of reflectance 0.2. The vertical line at an illuminance of 786 lx indicates the reference condition. At this illuminance, the apparent Munsell values of the surfaces have been normalized to their actual Munsell values. (After Jay, P.A., *Lighting Res. Technol.*, 3, 133, 1971.)

It is important to appreciate that even when the lighting conditions are such as to support it, perceptual constancy is not perfect. For example, lightness constancy will break down if large changes in illuminance occur. Figure 2.32 shows the apparent Munsell value of spectrally neutral surfaces plotted against the illuminance on the surfaces. It shows that as the illuminance is decreased, the apparent Munsell value, that is, the lightness, is reduced for all the Munsell samples, until at very low illuminances, all the Munsell values are in the range of dark grey to black (Munsell value <2). It should also be pointed out that this gradual breakdown in lightness constancy requires very large changes in illuminance relative to those that occur in interior lighting, which typically lie between 100 and 1000 lx.

2.5.2 Modes of Appearance

While lighting has an important role in preserving or eliminating constancy, it also has a role in determining the perceived visual attributes of a scene and the objects in it. Objects can have nine different attributes: brightness, lightness, hue, saturation, flicker, pattern, texture, gloss and clearness. Which attributes are perceived depends on the nature of the phenomenon being observed and the way it is lit (Cuttle, 2008). These attributes are defined as follows:

Brightness: an attribute based on the extent to which more or less light is seen to be emitted

Lightness: an attribute based on the extent to which more or less light is seen to be reflected

Hue: an attribute based on the classification of a colour as reddish, yellowish, greenish, bluish or their intermediaries or as having no colour

Saturation: an attribute based on the extent to which a colour is different from no colour of the same brightness or lightness

Flicker: an attribute based on the extent to which the phenomenon being observed is more or less stable

Pattern: an attribute based on the extent to which the phenomenon being observed is more or less uniform in appearance

Texture: an attribute based on the extent to which an object departs from a smooth surface

Gloss: an attribute based on the extent to which a surface is different from a matte surface with the same lightness, hue, saturation and clearness

Clearness: an attribute based on the extent to which colours are seen behind or within an object

Not all these attributes occur in every situation. Rather, different combinations of attributes occur in different modes of appearance. Modes of appearance can be classified at two levels (Cuttle, 2008). Table 2.2 summarizes these classifications with examples of each type. The first level is the division between located and non-located modes. The located mode implies that whatever is being perceived has a size and shape, while the non-located mode does not. Both located and non-located modes have illuminant and illumination modes. The illuminant mode occurs when the perception is of light alone. The illumination mode occurs when it is an illuminated surface that is being perceived. The located mode has a third mode associated with it. This is the object mode. This can come in two forms: surface and volume. The surface mode refers to an opaque surface seen by reflected light. The volume mode refers to a transparent or translucent object.

TABLE 2.2
Modes of Appearance

Mode Level 1	Mode Level 2	Example
Non-located	Illuminant	The sky; a fog
Non-located	Illumination	Ambient illumination of a room
Located	Illuminant	A luminaire; a computer screen
Located	Illumination	A beam of light
Located	Object–surface	A wall; a sheet of paper
Located	Object–volume	A glass vessel

Source: After Cuttle, C., *Lighting by Design*, Architectural Press, Oxford, U.K., 2008.

TABLE 2.3
Visual Attributes That Can Occur with Each Mode of Appearance

Attributes	Non-Located Illuminant	Non-Located Illumination	Located Illuminant	Located Illumination	Located Object–Surface	Located Object–Volume
Brightness	X	X	X	X	—	—
Lightness	—	—	—	—	X	X
Hue	X	X	X	X	X	X
Saturation	X	X	X	X	X	X
Flicker	X	X	X	X	—	—
Pattern	—	—	X	X	X	X
Texture	—	—	—	—	X	—
Gloss	—	—	—	—	X	—
Clearness	—	—	—	—	—	X

Source: After Cuttle, C., *Lighting by Design*, Architectural Press, Oxford, U.K., 2008.

Different attributes can be perceived in different modes of appearance. Table 2.3 shows which of the attributes are associated with each mode of appearance. Of particular interest to the perception of lighting is the shift between the attributes of brightness and lightness in different modes of appearance. Objects that are self-luminous, such as a computer screen or a luminaire, are perceived to have a brightness but not a lightness. In this located illuminant mode of appearance, the concept of reflectance is perceptually meaningless. However, when the same objects are turned off, they are in the located object–volume mode and do not have an attribute of brightness but do have a lightness in that their reflectances can be estimated. The attributes of brightness and lightness are mutually exclusive.

As with the constancies, limiting the amount of information available to the observer can change the attributes perceived. For example, by viewing the illuminated surface of an object through a small aperture so that the edges of the surface cannot be seen, the surface will be perceived to have a brightness rather than a lightness. When seen normally in the object mode, it will have a lightness but not a brightness. Such changes in perceived attributes are important because it implies that one of the main uses of lighting is to change the mode of appearance and hence the attributes perceived. For example, a painting hung on a wall has a lightness attribute when lighted so that both the painting and the wall appear in the object–surface mode. However, if the painting is illuminated solely with a carefully aimed framing spot so that the edge of the beam coincides with the edges of the painting, the painting takes on a self-luminous quality with a brightness attribute. Adjusting the modes of appearance is an important technique in display lighting, both indoors and outdoors.

2.6 SUMMARY

There is much about the higher reaches of the visual system that remains a mystery, but what is clear is that it involves both the eye and brain working together. The visual system consists of two parts: an optical system that produces an image on the retina of the eye and an image-processing system that extracts different aspects of that image at various stages along its progress from the retina to the visual cortex while preserving the location where the information came from. It is also clear that the visual system devotes most of its resources to analysing the central area of the retina, particularly the fovea. This implies that peripheral vision is mainly devoted to identifying something that should be examined in detail by turning the head and eyes so the image of whatever it is falls on the fovea.

The visual system can operate over a wide range of luminances, from sunlight to starlight. To do this, it continually adjusts its sensitivity to light, increasing its sensitivity as the amount of light available falls. Decreasing the amount of light from daylight to darkness takes the visual system through three distinct operating states: the photopic, the mesopic and the scotopic. In the photopic condition, fine discriminations of size and colour can be made. In the mesopic, the ability to make these discriminations deteriorates so that by the time the scotopic is reached, colour can no longer be seen, detail is impossible to discriminate and the fovea is blind. Interior lighting usually allows the visual system to operate in the photopic state, while exterior lighting often ensures the visual system is operating in the mesopic state. No lighting installation worthy of the name produces so little light that the visual system is in the scotopic state.

Like every other physiological system, the visual system has a limited range of capabilities. These limits are expressed by the thresholds of vision. A threshold is a stimulus that is detected at a specified percentage of the times it is presented, usually 50%. There are many different thresholds, one of the most common being visual acuity, that is, the smallest size of detail that can be resolved. Others quantify the smallest luminance contrast that can be detected, the smallest colour difference that can be detected and the lowest frequency of oscillation that can be seen. Different thresholds occur under different conditions of lighting and stimulus presentation, but in general, vision becomes more limited as the amount of light decreases, the stimulus occurs further away from the fovea and the degree of defocus increases. Threshold measurements provide well-defined and sensitive metrics to explore the operation of the visual system and so have been extensively used in the field of vision science, but for the practice of lighting, threshold measurements are mainly of interest for determining what will not be seen rather than how well something will be seen.

Given that the details of a scene are clearly visible, that is, they are well above their threshold values, the dominant characteristic of the visual system is the stability of perception in the face of continuous variation in the retinal image. Given lighting conditions that provide enough light with a wide spectral distribution in such a way that how the space is lit can be easily understood, the lightness, colour, size and shape of objects in the space remain constant no matter how they are viewed. It is only when the information about the space and the way it is lit is restricted or misleading that these perceptual constancies will break down. Lighting can be used to reinforce or to undermine the perceptual constancies. Lighting can also be used to reveal different attributes of objects, such as their brightness, lightness, hue, saturation, flicker, pattern, texture, gloss and clearness. Which of these attributes are revealed will depend on the characteristics of the phenomenon being observed and the way it is lit.

This chapter is not intended to be an exhaustive review of the visual system. There are many other books that explore this topic in much greater detail. If you are interested in doing so, you are recommended to see Purves and Beau-Lotto (2003), Sekular and Blake (2005) and Wolfe et al. (2006).

3 Non-Image-Forming System

3.1 INTRODUCTION

The obvious effect of light entering the eyes is to allow the visual system to operate but light entering the eyes affects many aspects of human physiology beyond vision. These effects of exposure to light are driven through what is becoming known as the non-image-forming system. The justification for this rather clumsy name is to emphasize the difference between these effects of light exposure and the visual system. The visual system is essentially an image-processing system. The non-image-forming system is not. Rather, the non-image-forming system refers to a complex of effects of light ranging from cell division and hormone production through other aspects of basic physiology to changes in behaviour, none of which depend on image processing. This chapter explores what is known about the non-image-forming system of humans.

3.2 SOME PHYSIOLOGY

That light has effects on human physiology and behaviour other than stimulating vision has been known for many years. What was not known was how these effects came about. Over the last two decades, some of the physiology behind these effects has been revealed. The main step forward in this area has been the identification of a new form of photoreceptor in the human retina (Berson et al., 2002; Berson, 2003). This new photoreceptor, called the intrinsically photosensitive retinal ganglion cell (ipRGC), is not found at the same level of the retina as the rod and cone photoreceptors used by the visual system. Rather, as its name suggests, it is a special form of ganglion cell (see Figure 2.5). The photopigment in the ipRGC is melanopsin (Kumbalasiri and Provencio, 2005). When extracted, melanopsin has a maximum absorption at a wavelength of 480 nm meaning it is most sensitive to short-wavelength light (Berson, 2007). Every ipRGC has an extensive dendritic arbour that spreads into the collector level of the retina, and these dendrites themselves respond to incident light (Berson et al., 2002). From measurements in the retinas of mammals such as mice and rats, it appears that these ipRGCs are relatively rare, being only 1%–2% of the retinal ganglion cells (Hattar et al., 2002). Further, they are distributed fairly evenly across the retina, although neither ipRGC nor their dendrites occur in the fovea where the cone photoreceptors are concentrated (see Figure 2.8). The ipRGCs have much slower response times than rod and cone photoreceptors, and because of their rarity and structure, the photon capture probability is much less than that of rod and cone photoreceptors (Do et al., 2009). This means that bright illumination is required to produce a sustained response so that the ipRGC can signal the retinal irradiance (Berson, 2003). Initially, it was thought that all ipRGCs were the same, but over the last few years, it has become apparent that there are a range of subtypes with different functions (Schmidt et al., 2011).

As for where the axon of each ipRGC goes, one answer is that, like other ganglion cells, they feed directly to several locations in the brain (Hattar et al., 2002). Figure 3.1 shows a simplified schematic diagram of the connections between the eye and the brain. There are two main routes that have been explored so far, the primary optic tract (POT) which is fed with signals from the cone and rod photoreceptors and leads to the visual cortex (see Figure 2.9) and the retino-hypothalamic tract (RHT) which is fed by signals from the ipRGC and leads to the suprachiasmatic nuclei (SCN). The SCN are recognized as the master clock in mammals, including humans (Klein et al., 1991). The SCN are responsible for synchronizing the timing of many different physiological events in the body including DNA repair and hormone production. Consequently, the SCN is connected to many other parts of the brain.

Figure 3.1 is simplified in that it suggests that the separation between the image-processing visual system fed from the cone and rod photoreceptors and the non-image-forming system fed from the ipRGC is total. It is not. Rather, it has

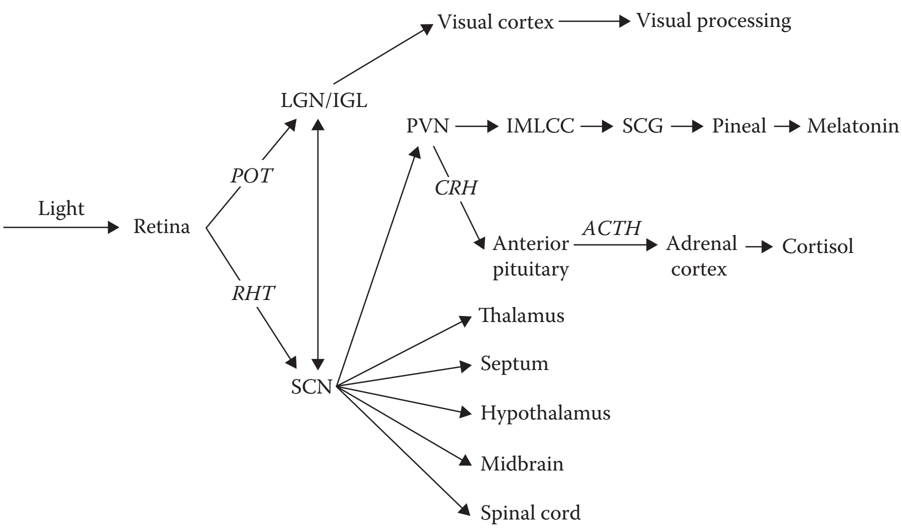

FIGURE 3.1 Schematic diagram of eye–brain pathways. Light received by the eye is converted to neural signals that pass via the optic nerve to two pathways, one visual and one non-visual. POT, primary optic tract; RHT, retino-hypothalamic tract; LGN/IGL, lateral geniculate nuclei/intergeniculate leaflet; SCN, suprachiasmatic nucleus of the hypothalamus; PVN, paraventricular nucleus of the hypothalamus; IMLCC, intermediolateral cell column; SCG, superior cervical ganglion; CRH, corticotropin-releasing hormone; ACTH, adrenocorticotropic hormone. (After Commission Internationale de l'Eclairage (CIE), *Ocular Lighting Effects on Human Physiology, Mood and Behaviour*, CIE Publication 158: 2004e and Erratum 2009, CIE, Vienna, Austria, 2004e.)

been found that the ipRGCs receive inputs from the rod and cone photoreceptors (Belenky et al., 2003; Perez-Leon et al., 2006; Hatori and Panda, 2010) and that outputs from the ipRGC are known to project to the brain centres that control pupil response (Dacey et al., 2005; Gamlin et al., 2007). There is also evidence for the exchange of signals between the SCN and the LGN of the POT (Dacey et al., 2005). This means that activities in the image-processing visual system and the non-image-forming system fed from the retina are mingled to some degree. The complexity this introduces to the task of fully understanding how exposure to light influences human behaviour and capabilities is only just beginning to be appreciated.

3.3 CIRCADIAN TIMING SYSTEM

The lives of living things are characterized by changes in behaviour that occur regularly over a 24 h cycle. As an example, consider the sleep–wake cycle present in all animals. These changes are called circadian rhythms, from the Latin words *circa*, about, and *dies*, day – about a day. Light entering the eye is a potent means for modifying the phase and amplitude of circadian rhythms. The nature of circadian rhythms was first explored by Jean-Jacques d'Ortous de Mairan in 1729 when he observed that the *heliotrope*, a plant that opens its leaves during the day and folds them at night, continued to do so even when kept in constant darkness. This implied that this observed behaviour was not simply a passive response to the external environment but must have an internal component. In 1866, William Ogle observed a similar phenomenon in humans when he noted that body temperature rose in the early morning and fell in the evening, regardless of the environment, but it was not until the 1930s that the concept underlying our understanding of the circadian timing system was promulgated by Bunning (1936). He suggested that circadian rhythms were driven by an endogenous (internal) clock that was entrained by an exogenous (external) signal such as the alternation of light and darkness (Kleinhoonte, 1929; Bunning and Stern, 1930). Bunning (1936) also hypothesized that this arrangement meant that interruptions of the normal light–dark cycle would shift the phase of the clock, the magnitude and direction of the phase shift being determined by when the interruption occurred. Specifically, exposure to bright light early in the night would lead to a phase delay, while bright light presented late in the night would lead to a phase advance.

Much research over the next 30 years showed that this concept was correct and that the basic endogenous/exogenous model occurred in many different forms of life (Gwinner, 1975; Pittendrigh, 1981). Among these life forms were humans (Sharp, 1960; Lobban, 1961; Aschoff, 1969). However, for many years, the potency of the light–dark cycle as an exogenous stimulus for humans was questioned until Czeisler et al. (1981) demonstrated that when light was provided at high illuminances and the dark cycle was truly dark, the light–dark cycle was a potent entrainment cue. Since then, many studies have shown that the exposure to light is a major exogenous stimulus for humans (Dijk et al., 1995) although it is not the only one. Some studies have shown that social cues (Aschoff et al., 1971), night-time activity (van Reeth et al., 1994) and exercise (van Someren et al., 1997a) may also impact entrainment. Conversely, some experiments with blind people have failed to show entrainment, even when the people lived in a conventional 24 h light–dark environment (Miles et al., 1977; Klein et al., 1993). How effective other regularly repeated stimuli are for entrainment remains an open question (Mistlberger and Skene, 2005; van Someren and Riemersma-van der Lek, 2007), but there can be little doubt that regular light–dark alternation is an effective exogenous stimulus for humans.

The circadian rhythm that has been most extensively studied in humans is the circadian timing system based on measurements of the hormone melatonin. Like the visual system, the circadian timing system starts with the eye, but unlike the visual system, it does not transmit information directly to the visual cortex. Rather, after leaving the eye, the circadian timing system proceeds up the RHT to the SCN and then by way of the paraventricular nucleus (PVN), the intermediolateral cell column of the spinal cord (IMLCC) and the superior cervical ganglion (SCG) to the pineal gland (Figure 3.2).

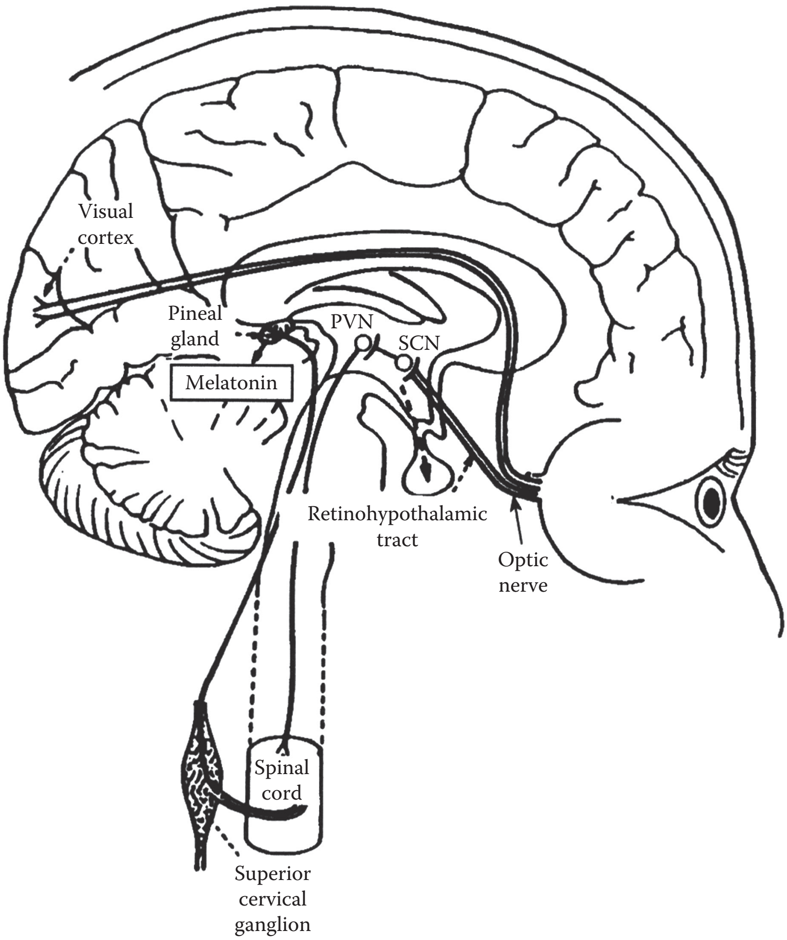

FIGURE 3.2 A simplified illustration of the retino-hypothalamic tract. (From Illuminating Engineering Society of North America (IESNA), *The Lighting Handbook*, 9th edn., IESNA, New York, 2000a.)

In dark conditions, the pineal gland synthesizes the hormone melatonin, which is then circulated throughout the body by the bloodstream where it is received by other peripheral clocks. Each element in this process will now be discussed in turn.

3.3.1 Retina

A detailed description of the structure of the retina of the eye is given in Chapter 2. Light reaching the retina provides signals to both the visual system and the circadian timing system but through different neural connections. For the visual system, there are four kinds of photoreceptors: three cone types, each with a different photopigment, and one rod type, with one photopigment different to any of the cones. The main photoreceptor type used to influence the human circadian timing system is the ipRGC with a different photopigment to either the rod or cone photoreceptors.

3.3.2 Suprachiasmatic Nuclei

Measurements of the response to light of SCN neurons in rats and cats indicate that they have very large receptive fields (20°–40°) with no on/off structure (Groos and Mason, 1980). Other measurements have shown that the output of the SCN in rats is characterized by a high threshold and a limited dynamic range, features that serve to convert the differences between night and day into a simple square wave (Groos and Meijer, 1985). The overall picture presented by these results is a simplification of the signals received from the retinal ganglion cells, in terms of a more limited dynamic range and greater spatial and temporal summation. This, together with the presence of photopigment in the dendritic arbour of the ipRGC, the relatively uniform distribution of ipRGC across the retina, the absence of any centre/surround receptive fields in the output of the SCN and the failure to maintain the location of signals arising from different ipRGC at the SCN, suggests that the ipRGC/SCN in combination essentially form a photocell signalling in the presence or absence of light. One of the places where this signal is sent is the pineal gland.

3.3.3 Pineal Gland

The pineal gland synthesizes and secretes the hormone melatonin during the dark phase of the 24 h light–dark cycle, regardless of whether the creature is diurnal or nocturnal in its activity pattern. Melatonin is easily absorbed into the bloodstream and hence serves as a chemical messenger throughout the body (Menaker, 1997). Melatonin receptors have been found in many parts of the body. The message carried by melatonin is that of darkness, as determined by the SCN, the master clock. The essential role of melatonin is to synchronize the activation of many other physiological functions, not to the same time, but rather to the times in the 24 h cycle when they should occur (Cagnacci et al., 1997). Normally, high levels of melatonin are secreted at night and low levels are secreted during the day (Figure 3.3). However,

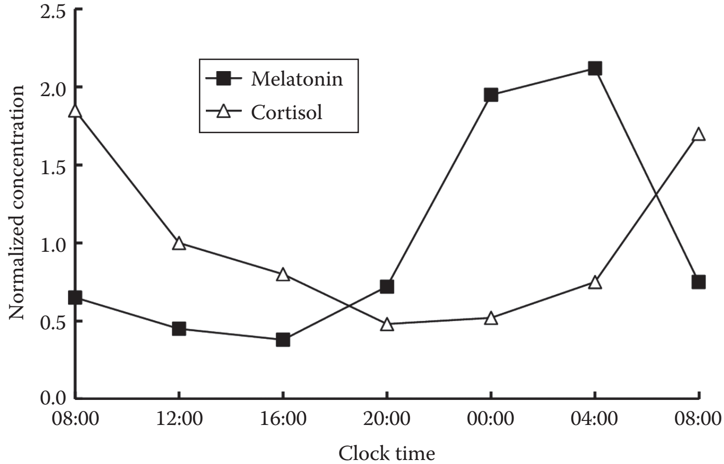

FIGURE 3.3 Normalized melatonin and cortisol concentrations in humans over 24 h. These data were collected from people kept awake at low light levels of 3 lx at the eye for the whole period. (From Figueiro, M.G. and Rea, M.S., *Int. J. Endocrinol.*, 2010, 829351, 2010.)

the presence of light at night suppresses the synthesis of melatonin, the amount of suppression being determined by the spectrum and the amount of retinal irradiance and the duration of exposure (Wood et al., 2013). As an example, Figure 3.4 shows the mean melatonin concentrations measured for six subjects at half hourly intervals between 10 p.m. and 5 a.m. Between midnight and 3 a.m., they were exposed to an illuminance at the eye of either 200, 400 or 600 lx (McIntyre et al., 1989). The reduction in melatonin concentration with exposure to light is clear, as is the recovery when the light is removed.

3.4 CHARACTERISTICS OF THE CIRCADIAN TIMING SYSTEM

The circadian timing system has a number of important characteristics. Probably, the most notable is the fact that it continues to oscillate even in the absence of any external cues to time. The average period of this oscillation in humans is slightly longer than 24 h (Czeisler et al., 1999). In the absence of external cues, these longer periods will occur over a number of days. When this happens, the circadian timing system is said to be free-running. Figure 3.5 shows the sleep–wake cycle measured for an individual over 20 days. For the first 5 days, time cues are present in the form of a regular light–dark cycle. For these 5 days, the period of the sleep–wake cycle is 24 h. For days 6–20, no time cues are present and the sleep–wake cycle starts to free-run with the result that after 20 days the individual is asleep in the middle of the day.

There can be little doubt that the presence of time cues, particularly a light–dark cycle, is necessary to prevent the circadian timing system from free-running, but the light–dark cycle has another role, to signal the passing of the seasons.

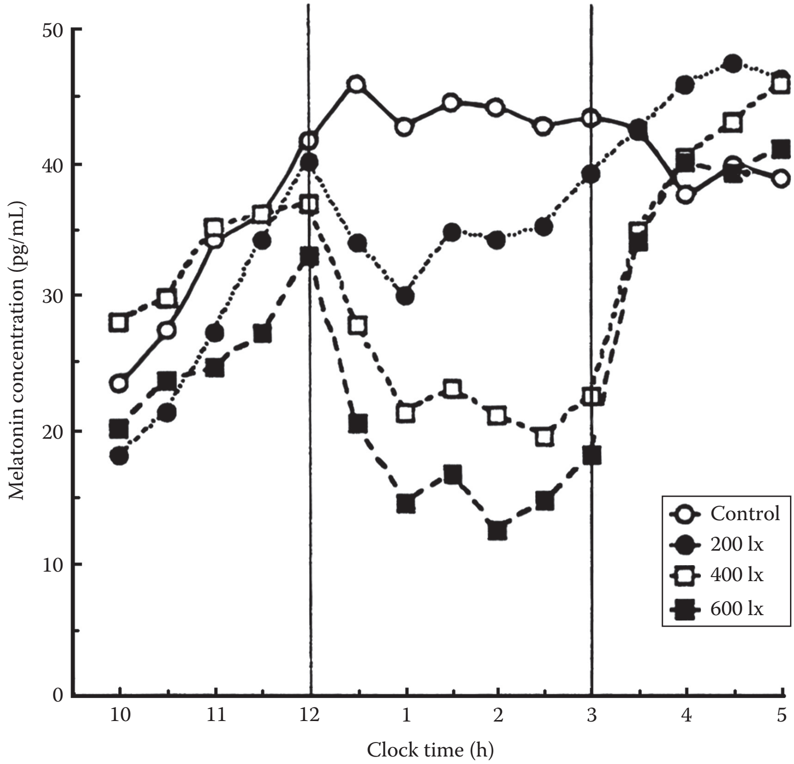

FIGURE 3.4 Melatonin concentrations at different times from 10 p.m. to 5 a.m. For the control condition, the subjects spent the entire period in a room where the illuminance was less than 10 lx. For the other conditions, the subjects spent the hours between 10 p.m. and midnight and between 3 and 5 a.m. in the room lit to less than 10 lx, but between midnight and 3 a.m., they were exposed to either 200, 400 or 600 lx at the eye. (After McIntyre, I.A. et al., *Life Sci*., 45, 327, 1989.)

Depending on the latitude at which you live, the length of the day and, conversely, the length of the night vary over the season. The longer is the night, the longer is the time for which melatonin is secreted. In animals that show distinct seasonal behaviour, there are cells that measure the duration for which melatonin is present (Bartness and Goldman, 1989). These cells also regulate seasonal changes in behaviour. It is interesting to note that rates of conception in humans exhibit seasonal variations (Roenneberg and Aschoff, 1990a,b), these variations being much larger before the industrial revolution (Bronson, 1995). This suggests that electric lighting can have an impact on the seasonal adjustment of the circadian system. Wehr et al. (1995) claim that most individuals who live in modern urban environments at temperate latitudes show no seasonal variation in duration of melatonin secretion. The implication of this is that the consistent use of electric light in the evening, after the sun has set and in the early morning before the sun has risen, suppresses melatonin secretion and therefore removes any seasonal variation (Wehr, 2001). Exactly how much exposure to electric light after dark is sufficient

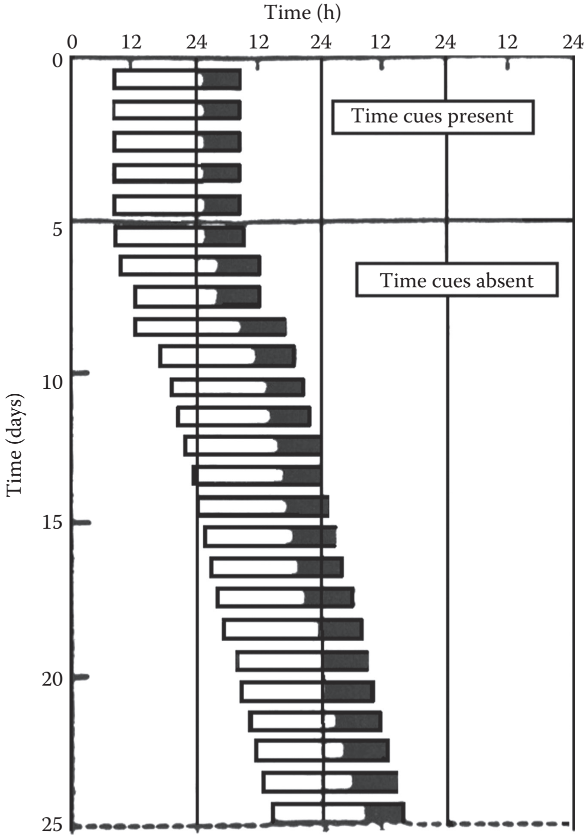

FIGURE 3.5 Sleep–wake cycles for an individual over 25 days, sleep periods being indicated by black shading. For the first 5 days, a constant light–dark cycle was present. At day 6 and for all the following days, a constant dim light level is provided throughout the 24 h. For the first 5 days, the period of the circadian cycle is 24 h, but after day 6, the period increases to more than 25 h and the circadian system starts to free-run resulting in a steady drift in sleep period.

to eliminate the effect of the naturally occurring seasonal variation in day length is an interesting question that has yet to be answered.

3.4.1 Phase Shifting

Figure 3.5 demonstrates that the primary effect of the light–dark cycle is to entrain the circadian timing system to a 24 h cycle. But what happens if the light–dark cycle is disrupted, say by light exposure during what is normally a period of darkness? The answer is a shift in the phase of the circadian rhythm. The direction of the phase shift depends on the timing of the light exposure. Figure 3.6 shows the phase response curves for a group of young (18–31 years) and older (59–75 years) men and women (Kripke et al., 2007). These phase response curves are based on a light exposure pattern in which the dark condition consisted of a repetitive alternating pattern

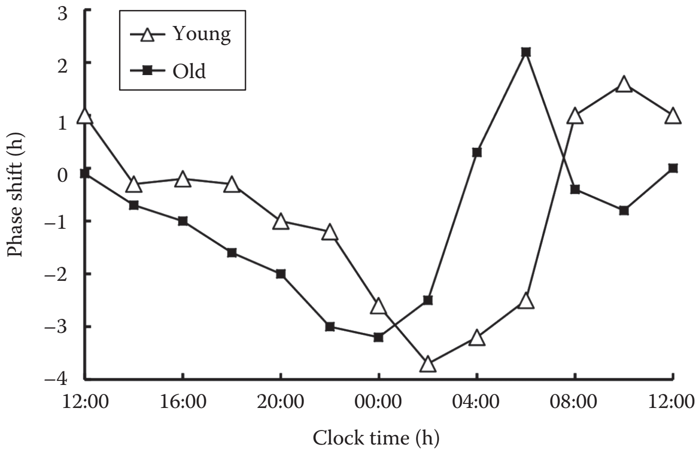

FIGURE 3.6 The phase response curves for a group of young (18–31 years) and older (59–75 years) men and women. (From Kripke, D.P. et al., *J. Circadian Rhythms*, 5, 4, 2007.)

of 30 min in bed in complete darkness with sleep encouraged followed by 60 min out of bed where normal social activities were allowed. The light exposure during this dark period was never more than 50 lx at the eyes when looking straight ahead. The light period was a 3 h exposure to 3000 lx at the eyes when looking straight ahead and was introduced at one of eight different times for three successive days. The light was provided by cool white (4100 K) fluorescent lamps. What these phase response curves show is that exposure to bright light during the afternoon has very little if any effect on the phase of the circadian cycle in the next 24 h. However, bright light given early in the night tends to delay the circadian cycle but bright light given late in the night tends to advance the phase of the circadian cycle. The critical time at which the effect of a pulse of bright light changes from a phase delay to a phase advance is around the minimum of the core body temperature which occurs 1–2 h before awakening. There is a clear difference between the two age groups with the older people moving from delay to advance at an earlier time than the younger group. There were no statistically significant differences between men and women in the same age group.

While the aforementioned understanding has been derived from a regime of strictly controlled light exposures, in everyday life, people are exposed to light at many different times of the night and day. Fortunately, there are several mathematical models of the effect of light exposure on the operation of the circadian timing system. The purpose of these models is to produce accurate predictions and testable hypotheses. Models applicable to humans have been developed by treating the link between lighting exposure and the phase of the circadian rhythm as a control theory problem (Kronauer, 1990; Forger et al., 1999; Kronauer et al., 1999; Antle et al., 2007). The early models were based on data for exposure to single bright light pulses. While these were capable of predicting the outcome of such exposure, they could not accurately deal with the effects of low light level exposure (approximately 100–200 lx) or of very bright (approximately 10,000 lx), short-duration (approximately 5 min) exposures separated by lengthy periods of darkness. The more recent models have been refined to accurately predict phase shifts to photopic stimuli of any temporal pattern and any illuminance in the photopic range. Yet, other models have been constructed based on the concept that exposure to light changes not only the phase and amplitude of the circadian system but also the period (Beersma et al., 1999). Currently, it is not clear which of these approaches is correct. For that to be established, some critical experiments testing the predictions of the models are required (Klerman and St Hilaire, 2007). Such critical experiments are important because studies have shown that intermittent exposure to bright light can be just as effective in phase shifting as continuous exposure (Rimmer et al., 2000; Gronfier et al., 2004). Further, such results suggest that the intermittent but brief exposures to light outdoors, typical of many modern lifestyles, are important for entrainment of the circadian timing system.

3.4.2 Melatonin Suppression

The phase-shifting effect of light exposure only becomes evident many hours after exposure. A more immediate and acute effect of light exposure at night is the suppression of melatonin synthesis (Figure 3.4). This results in an increase in alertness measured by a change in the nature of electroencephalograph (EEG) patterns, by

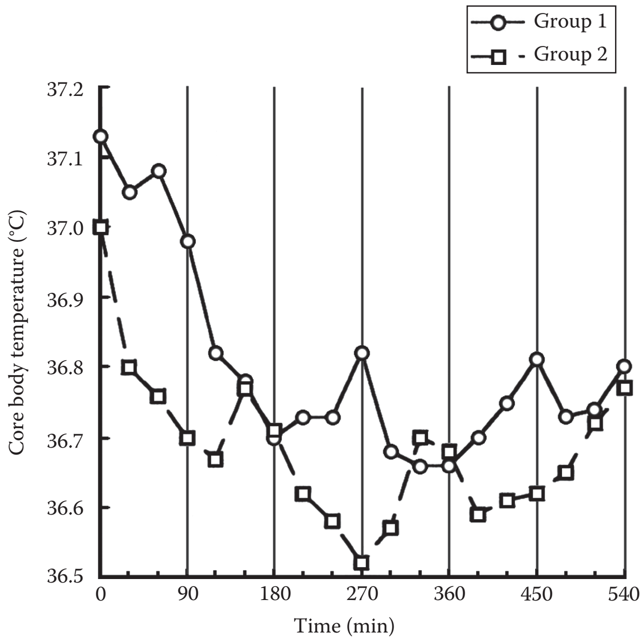

FIGURE 3.7 Modulation of the core body temperature by exposure to dim and bright light for alternating 90 min periods starting at midnight. Group 1 started with bright light. Group 2 started with dim light. (After Badia, P. et al., *Physiol. Behav.*, 50, 583, 1991.)

an increasing core body temperature and by reported feelings of alertness (Badia et al., 1991; Cajochen et al., 2000). Figure 3.7 shows the effect of exposure to bright (5000 lx) and dim (50 lx) light for alternate 90 min periods on core body temperature, starting at midnight. The overall trend of core body temperature to a minimum around 5 a.m. is obvious as is the modulation of that trend by the alternate exposure to bright and dim light. Exposure to bright light tends to increase the core body temperature, while dim light tends to reduce it.

3.4.3 Spectral Sensitivity

So far, the effects of light on phase shifting and melatonin suppression at night have been discussed using conventional photopic measures of light, such as illuminance at the eye. But measures of absorption by melanopsin have shown a peak sensitivity at about 480 nm which implies that photopic measures are not the right way to quantify the stimulus presented to the circadian system by light. What is required is a different measure based on the spectral sensitivity of the circadian system (Rea et al., 2010a). Two studies (Brainard et al., 2001; Thapan et al., 2001) independently measured the spectral sensitivity of the human circadian timing system using very narrowband light as a stimulus and the reduction in melatonin concentration, that is, melatonin suppression, as a response. By determining the amount of retinal irradiance required for a constant level of melatonin suppression, the spectral sensitivity at the wavelength of the stimulus can be calculated. Figure 3.8 shows the relative spectral sensitivities measured in these two studies. It is clear that melatonin

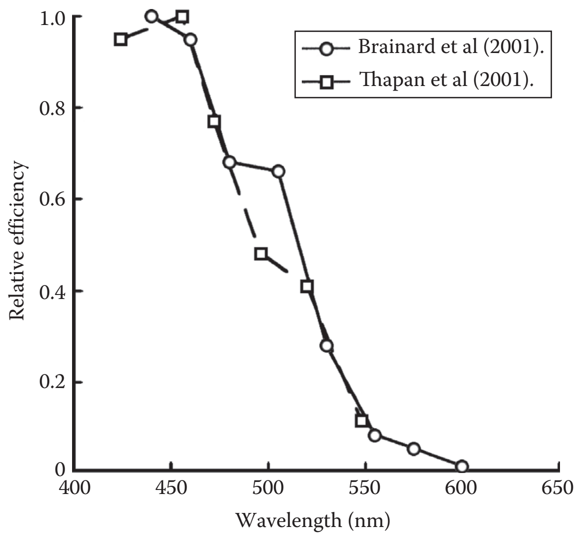

FIGURE 3.8 Measured relative efficiency of electromagnetic radiation at different wavelengths in stimulating the human circadian timing system, using melatonin suppression as a marker. (After Brainard, G.C. et al., *J. Neurosci.*, 21, 6405, 2001; Thapan, K. et al., *J. Physiol.*, 535, 261, 2001.)

suppression is primarily influenced by radiation at the short-wavelength end of the visible spectrum with a peak sensitivity at about 460 nm.

Both Brainard et al. (2001) and Thapan et al. (2001) fitted their data with a spectral sensitivity curve consistent with an opsin photopigment of the type found in the rod and cone photoreceptors. Unfortunately, when these curves were used to predict the effect of polychromatic light, that is, light made up of many different wavelengths, on melatonin suppression, the match to the measured results was not good (Figueiro et al., 2004, 2008a; Revell et al., 2012). To overcome this problem, a nonlinear model for circadian phototransduction suitable for both narrowband and polychromatic light has been developed (Rea et al., 2005b, 2012a). The model is designed to be consistent with the known photopigments and physiology of the human retina, including the spectral absorption of the lens, as well as fitting the data of Brainard et al. (2001, 2008) and Thapan et al. (2001). Figure 3.9 shows the spectral sensitivity given by this model. The nonlinear element of the model, which gives the discontinuity in the spectral sensitivity around 507 nm, has two components, an input from the blue–yellow opponent colour channel of the visual system (see Section 2.2.7) and a diode-like shunt that only allows input to the ipRGC when light has a spectrum that stimulates the S-cones more than the M- and L-cones. When light has a spectrum that stimulates the M- and L-cones more than the S-cones, input to the ipRGC is cut off. It remains to be determined if this model is worth the extra complexity relative to simpler linear models of Gall (2002) and Enizi et al. (2011) when it comes to predicting the effects of polychromatic light sources on melatonin suppression. The test of this model versus the simpler linear models requires particular attention to be paid to wavelengths in the range 470–510 nm where the various models most differ (Rea et al., 2012a).

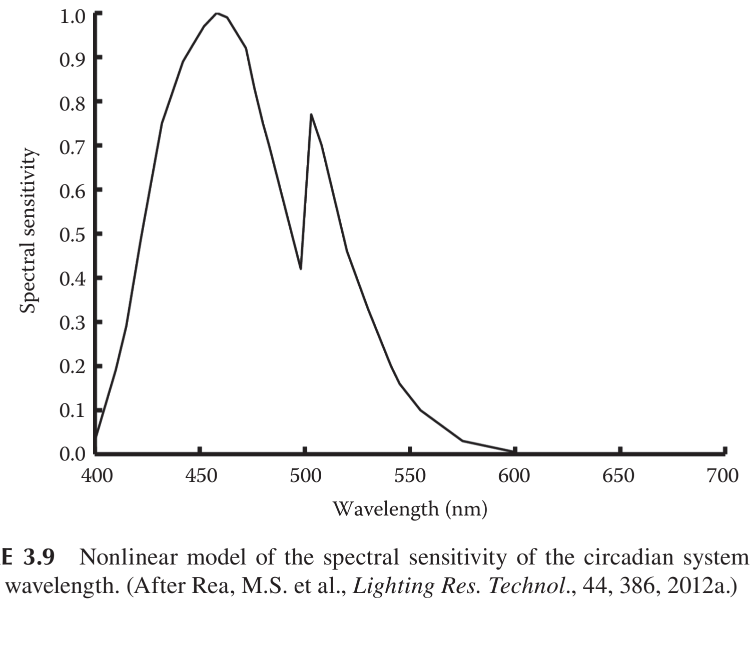

FIGURE 3.9 Nonlinear model of the spectral sensitivity of the circadian system plotted against wavelength. (After Rea, M.S. et al., *Lighting Res. Technol.*, 44, 386, 2012a.)

3.4.4 Amount of Light

Given that the spectral sensitivity is known, it is now possible to use the data of McIntyre et al. (1989), Brainard et al. (2001), Thapan et al. (2001), Rea et al. (2002) and Figueiro et al. (2004) to predict how much light is needed to suppress melatonin. Figure 3.10 shows the predicted percentage melatonin suppression occurring for a 1 h exposure at night to different illuminances at the eye delivered by an incandescent lamp and a D65 fluorescent lamp simulating daylight (Figueiro et al., 2006). The spectral sensitivity used to quantify the circadian stimulus provided by the two lamp spectra is the nonlinear model of Rea et al. (2005b). The two light sources have different curves because the two light sources have different light spectra, the D65 fluorescent having more power at the short-wavelength end of the visible spectrum than the incandescent. With a 1 h exposure to light, saturation of melatonin suppression appears to follow a compressive, nonlinear function with saturation at about 1000 lx and half saturation at about 300 lx. Figueiro et al. (2006) suggest that the threshold for melatonin suppression using incandescent lamps, a light source still widely used for lighting in homes, is 30 lx at the eye for 30 min.

Another measure of the effect of light exposure on melatonin suppression has been given by Zeitzer et al. (2000). They measured the phase shift of melatonin concentration and the percentage melatonin suppression for 6.5 h of light exposure to cool white fluorescent lamps at a fixed illuminance centred 3.5 h before the subject's minimum core body temperature. The illuminances at the eye during the light exposure ranged from 3 to 9100 lx. Figure 3.11 shows the melatonin phase shift and the melatonin suppression plotted against illuminance at the eye. Saturation of

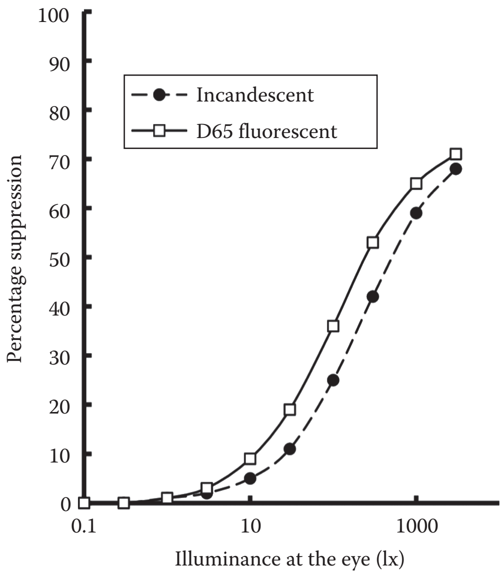

FIGURE 3.10 The predicted percentage melatonin suppression occurring for a 1 h exposure at night to different illuminances at the eye delivered by an incandescent lamp and a D65 fluorescent lamp simulating daylight. (From Figueiro, M.G. et al., *J. Carcinog.* 5, 20, 2006.)

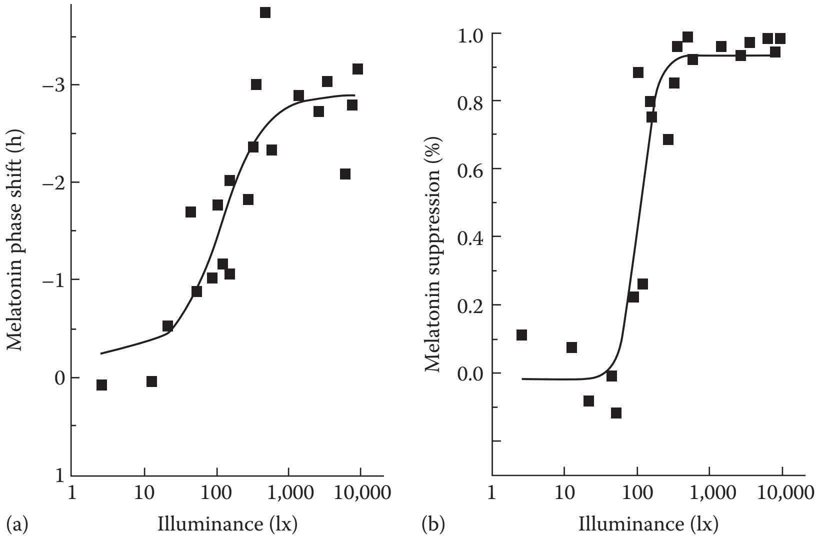

FIGURE 3.11 The effect of illuminance at the eye on (a) circadian phase shift of melatonin concentration and (b) percentage melatonin suppression, for 6.5 h of light exposure centred 3.5 h before the core body temperature minimum. (After Zeitzer, J.M. et al., *J. Physiol.*, 526, 695, 2000.)

suppression occurs at about 200 lx and half saturation occurs around 100 lx, values much less than predicted by Figueiro et al. (2006). This is not because the predictions of Figueiro et al. (2006) are wrong. Rather, it means that both the illuminance at the cornea and the duration of exposure matter for the effect of light on the circadian timing system. Further, they imply that, given a long enough exposure time, illuminances that occur in everyday lighting installations can be enough to entrain the human circadian system and may be the main source of entrainment for populations at high latitudes where daylight is limited for long periods and to many who live in urban areas, with limited exposure to daylight.

While these implications are important for understanding the impact of lighting installations on the circadian timing system, the illuminances shown should not be treated as definitive because of the difficulty in measuring light exposure in realistic situations. There are certainly devices now available for measuring the irradiance at the eye with approximately the right spectral sensitivity (Bierman et al., 2005; Hubalek et al., 2006; Figueiro et al., 2013a), but measuring the light received at the cornea is just the start of the problem. The quantity that matters for entraining the circadian system is the amount of light that reaches the retina, and the irradiance at the eye is at best an approximation to the retinal irradiance ignoring as it does the effects of pupil size and the transmittance of the ocular media. This is evident from the work of Brainard et al. (1997), who have shown that melatonin suppression is greater for dilated pupils than naturally changing pupils and greater for two eyes exposed than for one eye exposed, for the same illuminance on the cornea. Further, Dawson and Campbell (1990) have pointed out that in most lit spaces, the illuminance reaching the retina can vary dramatically depending on the light distribution, the reflectances of the surfaces forming the space and the direction of gaze. Thus, it is very difficult to know what the actual retinal irradiance is in realistic lighting situations, both indoors and outdoors, even at one moment in time. Given the variability introduced by the ability to look in different directions at different times, the possible errors of measurement become very large indeed. Further, it is the pattern of light exposure over the whole 24 h that determines the circadian response (Appleman et al., 2013). Even if the retinal irradiation could be measured accurately over a long period, there would still remain the problem of adaptation. There is evidence that the amount of light required to suppress a given percentage of melatonin is influenced by the prior history of exposure (Smith et al., 2004; Wong et al., 2005). For example, exposure to 4 h of daylight outdoors for a week increases the amount of light required to suppress melatonin at night. Finally, there is the question of individual sensitivity. The maximum concentration of melatonin produced in darkness can vary widely between individuals (Waldhauser and Dietzel, 1985).

Given all this uncertainty, it is not possible to state precisely how much light is necessary to influence the circadian timing system for a given exposure time, although, based on presently available data on acute melatonin suppression, the threshold of 30 lx for 30 min from an incandescent light source proposed by Figueiro et al. (2006) seems a plausible working hypothesis. Despite the uncertainty, what is clear is that it is the irradiation of the retina that matters. Whether that irradiation originates from natural light or electric light is immaterial, although the actual spectrum is obviously important. It is also clear that, given a long enough duration, current lighting practice often provides enough stimulation to the circadian timing system to modify its operation.

3.5 AWAKENING SYSTEM

The non-image-forming system is more than just the circadian timing system. Another component affected by exposure to light is the production of the hormone cortisol (Figure 3.1). One route for this to occur is when signals from the ipRGC are transmitted to the SCN and then to the PVN of the hypothalamus and so via the anterior pituitary gland to the adrenal cortex which generates cortisol. The role of cortisol is to release the energy needed to achieve the transition from inactivity to activity, as a routine or as a response to stress. Given that we make a transition from inactivity to activity every morning on waking, it should not come as surprise that cortisol has a clear circadian rhythm. Figure 3.3 shows the cycle of cortisol concentration found in humans over 24 h spent in dim lighting (Figueiro and Rea, 2010). There is a peak concentration around the time of waking which declines slowly until it reaches its nadir in the first part of the night, a nadir that is maintained until the early morning. It has been argued that cortisol serves to prepare the body for activity on waking, and this is certainly true as there is a steady increase in cortisol concentration prior to waking but it is not the whole truth. It is also possible that waking triggers hormone release as there is a sharp increase in cortisol concentration about 30 min after waking, called the cortisol awakening response (Wust et al., 2000).

Given that the adrenal cortex producing cortisol receives an input from the SCN and the SCN itself is entrained by the alternating exposure to light and dark, it should not be surprising to find that exposure to light at specific times has been shown to advance or delay the phase of the cortisol rhythm (Boivin and Czeisler, 1998). But can light exposure acutely affect cortisol in the same way as it suppresses melatonin? The answer is yes but the magnitude and direction of the effect is uncertain. Leproult et al. (2001) showed that exposure to illuminances in the range 2000–4500 lx for 3 h between 5 and 8 a.m. induced an immediate elevation in cortisol concentration. Figueiro and Rea (2010) also found that exposure to 40 lx of both narrow-band short-wavelength and long-wavelength light produced an increase in cortisol concentration at night. However, Jung et al. (2010) measured the effect on cortisol concentration of exposure to 10,000 lx at the eye for 6.7 h during the night and morning, that is, when cortisol concentration was high, and found an acute suppression of cortisol. Clearly, there is much still to be learnt about the effect of light exposure on cortisol concentration covering such variables as the spectrum, amount, duration and timing of the exposure.

So far, the circadian rhythm of cortisol has been discussed as though it was simply an inverse of melatonin but it is much more than that. For a start, while melatonin production is concentrated in times of darkness for both diurnal and nocturnal creatures, cortisol production is concentrated at the start of activity which is at sunrise for diurnal creatures like humans and at sunset for nocturnal creatures like rats. In a way, this can be considered as an example of the power of the circadian timing system to time the activity of other hormone-generating systems according to the nature of the creature in question.

Further, cortisol concentration can be dramatically increased when stressful events occur (Baum and Grunberg, 1997). These events can be sensory or psychological. The increase in cortisol concentration can occur at any time and can occur quickly. This fast response is taken to be a way of mustering the energy necessary to deal with the cause of the stress. The existence of a fast response at any time that can be driven by all the senses, not just vision, suggests that there must be routes other than through the SCN whereby cortisol concentration can be impacted. This possibility is supported by the finding that both short-wavelength (blue) and long-wavelength (red) irradiation can increase cortisol concentration (Figueiro and Rea, 2010), but only short-wavelength irradiation suppresses melatonin. This raises a number of interesting questions. What is the physiological route or routes by which this fast response occurs? Is it that the circadian cycle of cortisol driven by the SCN is a baseline on which the experiences of the waking day impose their influence? What is the spectral sensitivity of cortisol suppression? Given that both short-wavelength and long-wavelength light can influence cortisol concentration, it cannot be the same as the circadian timing system. How much light is required to change cortisol concentration? Can it be achieved with illuminances and spectra closer to those likely to be delivered by conventional indoor lighting? These are just some of the many questions that remain to be answered as to the effects of light exposure on the neuroendocrine systems of humans, but the fact that they are being asked at all demonstrates how far our understanding of the non-image-forming effects of light has come over the last decade.

3.6 PUPIL SIZE

So far, this discussion of the non-image-forming system has concentrated on the role of light exposure on the circadian timing system and the awakening system, but it is also necessary to remember that some ipRGCs, believed to be a distinct subpopulation (Chen et al., 2011), are connected to parts of the brain that impact the non-image-forming operations of the visual system. One that has been extensively studied is the pupil (Zele et al., 2011). The pupil of the eye varies in size according to the amount of light received at the retina. As the amount of light reaching the retina increases, the diameter of the pupil deceases. Conversely, when the amount of light reaching the retina decreases, the pupil diameter increases. This is part of the process of adaptation whereby the visual system adjusts its sensitivity to match the prevailing environmental conditions (see Section 2.3.1). Until recently, it was assumed that this adaptation process was driven by signals from the rod and cone photoreceptors alone, but now it is known that some ipRGCs project to the LGN and then to the pretectal olivary nucleus, a part of the brain involved in the pupillary light reflex (Dacey et al., 2005). This explains why Gamlin et al. (2007) were able to find that when signals from rod and cone photoreceptors were blocked, the pupil response was maintained during continuous illumination, a finding which implies that the ipRGCs have a role to play in determining pupil size. This should not be taken to mean that pupil size is controlled by ipRGC alone. Rather, it means that all three photoreceptor types, rods, cones and ipRGC, are involved in different combinations depending on the amount of light and the time after the change in light level. Given a sudden switch off of illumination from a photopic level, the pupil will dilate, this process being driven by the cone and rod photoreceptors alone, the ipRGC response time being too slow to influence the immediate response. However, after about 10 s, the ipRGCs come into operation and influence what is called the post-illumination pupil response. As time increases, the rod and cone photoreceptor activity decreases leaving the ipRGC as the main influence on the sustained pupil size. This is probably why Bouma (1962) found that measurements of the spectral sensitivity of the eye based on pupil size produced a response function with a peak close to the peak sensitivity of the ipRGC.

While this may be valuable knowledge from the point of view of physiology, it would be of little interest here was it not for the fact that pupil size has an influence on visual acuity (Berman, 2008). At the same luminance, light spectra that contain more short-wavelength radiation have been found to improve visual acuity (Berman et al., 2006). The usual approach to improving visual acuity is to increase the illuminance, but such findings suggest that the same end can be achieved by changing the light spectrum to provide greater stimulation of the ipRGC (see Section 7.3.2.2).

Although the variations of pupil size with retinal illumination are well understood and the roles of the different photoreceptors are well under way to being understood, it is necessary to point out that such variations are really the baseline on which other factors may act. Among the emotional factors that can influence pupil size are pain, surprise, pleasure and stress. In other words, how the brain perceives what is happening moment to moment and what that means will also influence pupil size. Further, the information required to generate pain, surprise, pleasure and stress can all arise through any of the body's sensory systems or internally within brain activity. This reinforces an important point, namely, that many of the body's non-visual manifestations of the effects of light are influenced by multiple factors, many of which do not involve light.

3.7 PROBLEMS AND POTENTIAL

Our understanding of the non-image-forming system is developing rapidly but much remains to be determined. This is partly because there are many possible pathways yet to be explored (Figure 3.1) and partly because the effects of light exposure can be measured in many different ways. Measurements of the consequences of exposure to light at different times have ranged from changes in hormone concentrations (Figueiro and Rea, 2010), through changes in brain activity patterns (Lockley et al., 2006), core body temperatures (Badia et al., 1991) and pupil size (Chen et al., 2011), to feelings of sleepiness and alertness and even task performance (Figueiro and Rea, 2011). This range of measurement types occurs because of the diversity of expertise and interests involved in the field. Some are neurologists and physiologists, others are ergonomists and psychologists. Some are concerned to understand the pathways of the non-image-forming system. Others are concerned with how best to apply light exposure for practical purposes. Often, a number of different measurements are made so as to use a converging operations approach to proof (see Section 17.6). One thing that is certain is that the characteristics of different pathways through the non-image-forming system will be different for different measures.

At the moment, the overall picture of the non-image-forming system is like a part-completed jigsaw. Some parts are beginning to make sense but others are still a mystery with a lot of unconnected pieces yet to be placed in position. One such part is the effect of light exposure on the hormone serotonin, a hormone that has a distinct circadian rhythm and that is connected to mood. The fact that serotonin has a circadian rhythm implies that it may be influenced by exposure to light. It is also worth noting that, as well as signals from the retina, the SCN is known to receive signals from the LGN and from the raphe in the brain stem where serotonin is produced (de Pontes et al., 2010). How these three inputs to the SCN interact is not clear.

Another area of interest is the effect of light exposure during the day. Viola et al. (2008) have found that exposure to short-wavelength-rich light during the day can have an effect on alertness but so does long-wavelength-rich light (Sahin and Figueiro, 2013). This cannot be due to melatonin suppression because during the day, melatonin concentration is at a low level; so what is the mechanism? It could be that blue or red lighting is unusual, so alertness is being generated by the novelty of the environment but it might be a direct effect through a route as yet unexplored, a route that is likely to differ in characteristics from those established for melatonin suppression.

Even the circadian timing system still has some characteristics requiring answers. For example, the amount of light required to produce a given amount of melatonin suppression is known to be influenced by prior light exposure (Hebert et al., 2002), the photoreceptors involved can vary with the amount and duration of light exposure (Gooley et al., 2010), there may be variations in the spectral sensitivity over the 24 h (Figueiro et al., 2005), it is suspected that the ipRGCs are not equally distributed across the upper and lower parts of the retina (Glickman et al., 2003) and there are considerable individual differences (Duffy and Wright, 2005).

Until such fundamental and applied aspects of the non-image-forming system are fully understood, it would be as well not to attempt to implement practical applications widely. There are a number of reasons for caution. The first is the possibility of long-term adverse side effects produced by manipulation of different parts of the non-image-forming system. The non-image-forming system, particularly the circadian timing system, operates at a very basic level of human physiology and interacts with many other components of that physiology. The nature of these interactions needs to be understood. One example of the concerns that bright light exposure at night can raise is the hypothesis that suppressing melatonin is associated with an increased likelihood of breast cancer (see Section 14.5.1).

Although caution in application is wise, it would be equally unwise to neglect the potential that using light to manipulate the non-image-forming system has for enhancing human health and performance. An obvious application is to use the ability to shift the phase of the circadian system to rapidly adjust to the need to work at times when one would normally be sleeping, for example, when starting or finishing night-shift work (Eastman, 1990; Boivin and James, 2002) or after long transmeridianal flights (Houpt et al., 1996). Less obvious is the use of light for the treatment of elderly people suffering from dementia (Riemersma-van der Lek et al., 2008). Installing high illuminances in care homes where such people live has resulted in a modest improvement in both cognitive and non-cognitive symptoms of dementia (see Section 14.4.3). This is a reasonable application because, to put it bluntly, there is no long-term risk and anything that makes the lives of people with dementia better is worthwhile.

A more general approach that would have practical benefits would be to seek out existing working and lighting conditions that lead to circadian disruption and change them. Circadian disruption is known to have adverse consequences for human health (Klerman, 2005; Stevens et al., 2007). One situation that is known to cause circadian disruption and is associated with poor health consequences is working rapidly rotating shifts (Miller et al., 2010; Schernhammer and Thompson, 2011). To identify circadian disruption does not require detailed knowledge of how the non-image-forming system works. It simply requires knowledge of what the circadian timing rhythm should be under the natural conditions of light by day and darkness at night. By seeking out the type of shift system and the associated light exposure pattern that minimizes circadian disruption, the health of many working people could be improved.

3.8 SUMMARY

Light entering the eyes affects many aspects of human physiology beyond vision. These effects are driven through the non-image-forming system, a name designed to emphasize its difference from the visual system, which is essentially an image-processing system.

The non-image-forming system starts from a new photoreceptor only discovered this century and is called the ipRGC. The photopigment in the ipRGC is melanopsin which has a maximum absorption at 480 nm. Every ipRGC has an extensive dendritic arbour that spreads into the collector level of the retina, and these dendrites themselves respond to incident light. Further, the ipRGCs network has a high threshold and a slow but sustained output when stimulated. These characteristics make the ipRGC network well suited to signal light level to the brain. Initially, it was thought that all ipRGCs were the same, but over the last few years, it has become apparent that there are a range of subtypes with different functions.

Many ipRGCs send signals to the suprachiasmatic nuclei SCN of the hypothalamus of the brain. The SCN are recognized as the master clock in mammals, including humans. The SCN are responsible for synchronizing the timing of many different physiological events in the body including DNA repair and hormone production. Consequently, the SCN are connected to many other parts of the brain. Not all these connections have been investigated but two that have are the circadian timing system and the awakening system.

The role of the circadian timing system is to establish an internal replication of external night and day. The human circadian timing system involves three components: an internal (endogenous) oscillator, located in the SCN; a number of external (exogenous) oscillators that can reset (entrain) the SCN; and a messenger hormone, melatonin, that carries the internal *darkness* information to other oscillators in all parts of the body through the bloodstream. In the absence of light, and other cues, the internal oscillator continues to operate but with a period slightly longer than 24 h. External stimuli are necessary to entrain the SCN to a 24 h period and to adjust for the seasons.

The light–dark cycle is one of the most potent of the external stimuli used for entrainment. By varying the amount of light exposure and when it is presented, it is possible to shift the phase of the circadian timing system, either forward or backward, as required. In addition, it is possible to have an immediate alerting effect at night by suppressing melatonin. The amount of light required to cause these effects is within the range of current indoor lighting practice. The spectral sensitivity of the circadian system peaks around 460 nm so it is very different from the CIE standard photopic Observer, the most widely used definition of light. This implies that spectra that have a lot of power at the short-wavelength end of the visible spectrum will require lower illuminances to produce the same effect on the circadian timing system.

As for the awakening system, this involves the hormone cortisol. The role of cortisol is to release the energy needed to achieve the transition from inactivity to activity. For humans, cortisol has a circadian rhythm peaking just after awakening and then fading away to a minimum in the early night. Cortisol is produced by the adrenal gland, its timing being partly governed by the SCN. Unlike melatonin which is relatively immune from transitory external influences other than light, cortisol concentration can be dramatically and rapidly increased when stressful events occur. These events can be sensory or psychological. This fast response is taken to be a way of mustering the energy necessary to deal with the cause of the stress and implies that there must be at least one route other than through the SCN whereby cortisol concentration can be impacted.

Although many aspects of the non-image-forming system remain to be investigated, one feature that is clear is that it is not isolated from the visual system. It is known that the ipRGCs receive inputs from the rod and cone photoreceptors and that outputs from the ipRGCs project to the brain centres that control non-imaging parts of the visual system. This means activity in the visual and non-image-forming systems fed from the retina is mingled to some degree.

One aspect of the non-image-forming system that has implications for lighting practice is the ability to shift the phase of the circadian system. This should make it possible to rapidly adjust to the need to work at times when one would normally be sleeping, for example, when starting or finishing night-shift work or after long transmeridianal flights. But caution is advisable when considering such action. The fact is there is still much to learn about the form and characteristics of the non-image-forming system. The non-image-forming system, particularly the circadian timing system, operates at a very basic level of human physiology. Until all the possible interactions between the elements of the system are understood and any adverse side effects are identified, it would be as well to be cautious about attempting to use light to manipulate such a fundamental part of our physiology. The only rational approach at present is to identify working conditions that cause disruption of the circadian timing system. Frequent circadian disruption is associated with poor health, so reducing its occurrence would be beneficial.

Section II

Generalities

4 Lighting and Work

4.1 INTRODUCTION

Millions of people spend a significant part of their lives working. Electric lighting is provided at their workplaces to ensure that they can see to do their work quickly, accurately and easily. Thus, the provision of lighting has an economic impact beyond the cost of equipment, installation and power. Further, in many countries, the cost of providing the lighting at a work place is miniscule relative to other costs. For example, in the United States, the annual cost of lighting a 10 m^2 office is typically less than 0.1% of the cost of paying someone to occupy that office (New Buildings Institute, 2010). This means that only a small change in task performance is required to economically justify a large change in lighting practice. This chapter describes what is known about the relationship between lighting and work.

4.2 OVERVIEW

To understand the relationship between lighting and work, it is first necessary to identify the routes by which lighting can affect human performance. There are three such routes: through the visual system, through the circadian timing system and through mood and motivation. Figure 4.1 shows a conceptual framework for considering the factors that influence progress down each route and the interactions between them.

The effect of lighting on vision is the most obvious impact of light on humans. With light we can see, without light we cannot. The visual system is an image-processing system. The optics of the eye form an image of the outside world on the retina. At the retina, some image processing occurs. Different aspects of the retinal image are processed through different channels up to the visual cortex of the brain. The magnocellular channel processes information rapidly but with little detail or colour information, while the parvocellular and koniocellular channels provide details of brightness, colour and texture but at a slower rate. In addition, the visual system is organized spatially into two parts, the fovea of the retina, where fine detail is available, and the periphery, which is basically a detection system indicating where in the visual field the fovea should be directed. When there is a lot of light available, for example, in daytime, the whole of the retina is active. When there is very little light, for example, outside on a moonless night, the fovea is blind and only the peripheral retina operates. A more detailed discussion of the visual system is given in Chapter 2.

Any stimulus to the visual system can be described by five parameters: its visual size, luminance contrast, colour difference, retinal image quality and retinal illuminance. These parameters are important in determining the extent to which the visual system can detect and identify the stimulus.

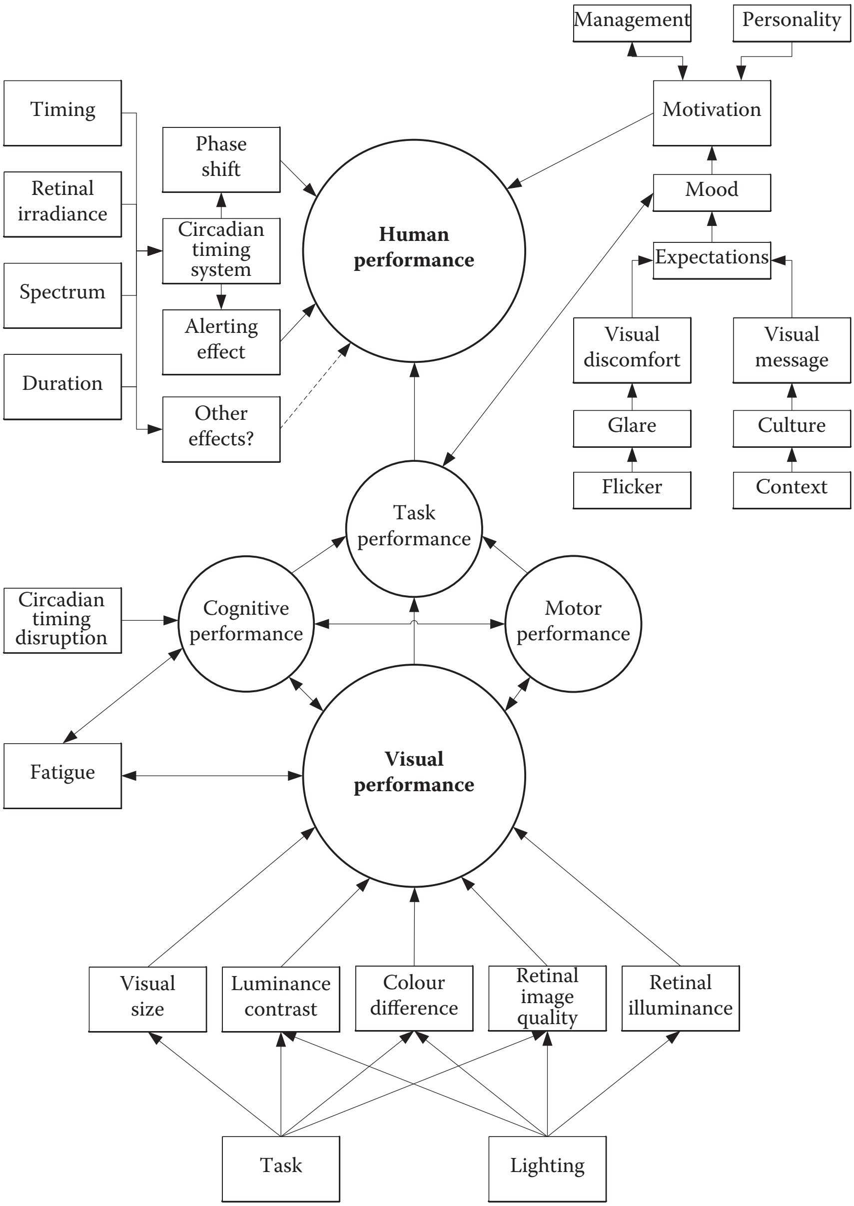

FIGURE 4.1 A conceptual framework setting out the three routes whereby lighting conditions can influence human performance. The arrows in the diagram indicate the direction of effect.

Visual size: There are several different ways to express the size of a stimulus presented to the visual system but all of them are angular measures. The visual size for detection is usually given by the solid angle the stimulus subtends at the eye. The solid angle is given by the quotient of the areal extent of the object and the square of the distance from which it is viewed. The larger is the solid angle, the easier the stimulus is to detect.

The visual size for resolution is usually given as the angle the critical dimension of the stimulus subtends at the eye. What the critical dimension is depends on the stimulus. For two points, the critical dimension is the distance between them. For two parallel lines, it is the separation between the two lines. For a Landolt ring, it is the side of the square forming the gap in the ring. The larger is the visual size of detail in a stimulus, the easier it is to resolve that detail.

For complex stimuli, the measure used to express the dimensions is the spatial frequency distribution. Spatial frequency is the reciprocal of the angular subtense of a critical detail, in cycles per degree. Complex stimuli have many spatial frequencies and hence a spatial frequency distribution. The match between the luminance contrast at each spatial frequency of the stimulus and the contrast sensitivity function of the visual system determines if the stimulus will be seen and what detail will be resolved (see Section 2.4.3). Lighting can do little to change the visual size of 2D objects, but shadows can be used to enhance the effective visual size of some 3D objects (see Section 8.5).

Luminance contrast: The luminance contrast of a stimulus expresses its luminance relative to its immediate background. The higher is the luminance contrast, the easier it is to detect the stimulus. There are several different forms of luminance contrast (see Section 2.4.1.1) so it is always necessary to know which definition is being used. Lighting can change the luminance contrast of a stimulus by altering the luminances of its components and by producing disability glare in the eye or veiling reflections from the stimulus.

Colour difference: Luminance quantifies the amount of light emitted from a stimulus but ignores the combination of wavelengths making up that light. It is the wavelengths emitted from the stimulus that influence its colour appearance. It is possible to have a stimulus with zero luminance contrast that can still be detected because it differs from its background in colour. There is no widely accepted simple measure of colour difference, although a number of metrics have been constructed from the location of the object and the immediate background in the various Commission Internationale de l'Eclairage (CIE) colour spaces (see Section 1.6.1). Lighting can alter the colour difference between the object and its background when light sources with different spectra are used.

Retinal image quality: As with all image-processing systems, the visual system works best when it is presented with a sharp image. The sharpness of the stimulus can be quantified by the spatial frequency distribution of the stimulus: a sharp image will have high spatial frequency components present; a blurred image will not.

The sharpness of the retinal image is determined by the stimulus itself, the extent to which the medium through which light from the stimulus is transmitted scatters light and the ability of the visual system to focus the image on the retina. Lighting can do little to alter any of these factors, although it has been shown that light sources that are rich in the short wavelengths produce smaller pupil sizes for the same luminance than light sources that are deficient in the short wavelengths (see Section 3.6). A smaller pupil size produces a better quality retinal image because it implies a greater depth of field and weaker spherical and chromatic aberrations.

Retinal illuminance: The illuminance on the retina determines the state of adaptation of the visual system and therefore alters the capabilities of the visual system (see Chapter 2). The retinal illuminance produced by a surface luminance is determined by the equation

$$E_r = e_t t \left(\frac{\cos \theta}{k^2} \right)$$

where
- E_r is the retinal illuminance (lx)
- t is the ocular transmittance
- θ is the angular displacement of the surface from the line of sight (degrees)
- k is a constant equal to 15
- e_t is the amount of light entering the eye (trolands)

$$e_t = L \cdot \rho$$

where
- L is the surface luminance (cd/m^2)
- ρ is the pupil area (mm^2)

The amount of light entering the eye, e_t, measured in trolands, is often referred to as retinal illumination but it does not take the transmittance of the optic media into account and therefore does not truly represent the retinal illuminance. The amount of light entering the eye is mainly determined by the luminances in the field of view. For interiors, these luminances are determined by the reflectances of the surfaces in the field of view and the illuminances on them. For exteriors, the relevant luminances are those of reflecting surfaces, such as the ground, and of self-luminous sources, such as the sky.

What these five parameters imply is that it is the interaction between the object to be seen, the background against which it is seen and the lighting of both object and background that determines the stimulus the object presents to the visual system and the operating state of the visual system. It is the stimulus and the operating state of the visual system that determine the level of visual performance achievable, but this is not the end of the story. Most apparently, visual tasks have three components: visual, cognitive and motor. The visual component refers to the process of extracting information relevant to the performance of the task using the sense of sight. The cognitive component is the process by which sensory stimuli are interpreted and the appropriate action determined. The motor component is the process by which the stimuli are manipulated to extract information and/or the actions decided upon are carried out. These three components interact to produce a complex pattern between stimulus and response leading ultimately to task performance. Further, every task is unique in its balance between visual, cognitive and motor components and hence in the effect lighting conditions have on task performance. It is this uniqueness that makes it impossible to generalize from the effect of lighting on the performance of one task to the effect of lighting on the performance of another. The effect of lighting on the performance of a specific task depends on the structure of the task and specifically the place of the visual component relative to the cognitive and motor components. As a general rule, tasks in which the visual component is large will be more sensitive to changes in lighting conditions than tasks where the visual component is small. Implicit is the fact that visual performance and task performance are not necessarily the same. Task performance is the performance of the complete task. Visual performance is the performance of the visual component of the task. Task performance is what is needed in order to measure productivity and to establish cost/benefit ratios comparing the costs of providing a lighting installation against the benefits of improved task performance. Visual performance is the only thing that changing the lighting conditions can affect directly.

Another route whereby lighting conditions can affect work is through the non-image-forming system (see Chapter 3). There are many aspects of this system, which still require study, but until they have been fully investigated, their effects on human performance remain a possibility rather than a fact. The one aspect of the non-image-forming system that is definitely known to influence human performance is the circadian timing system. The most obvious external evidence for the existence of a circadian timing system in humans is the occurrence of the sleep–wake cycle, but this is only the tip of the iceberg. Beneath the surface lie the variations in many different hormonal rhythms over a 24 h period. The organ that controls these cycles in humans is the suprachiasmatic nucleus (SCN). The SCN is linked directly to the retina. When signals are transmitted from the retina to the SCN, no attempt is made to preserve their original location. Rather, the network of intrinsically photosensitive retinal ganglion cell (ipRGC) in the retina that supplies the SCN acts like a slow-response photocell. This means that the aspects of lighting that influence the state of the SCN are the amount and spectrum of the radiation reaching the retina as well as the timing and duration of exposure.

There are two distinct ways by which light, operating through the circadian timing system, might be used to improve the performance of a tasks: a phase-shifting effect in which the phase of the circadian rhythm can be advanced or delayed by exposure to bright light at specific times (Dijk et al., 1995) and an acute effect related to the suppression of the hormone melatonin at night that increases alertness (Campbell et al., 1995). There has also been interest in seeing if exposure to light during the day can enhance the performance of tasks by manipulating the hormone cortisol. There is certainly evidence that exposure to a high light level soon after awakening increases cortisol concentration (Scheer and Buijs, 1999) but the implications for what happens during the rest of the day are unclear. Ruger et al. (2006) exposed people to 5000 lx between noon and 16.00 h and found no effect on cortisol concentration but a positive effect on alertness. Similarly, Kaida et al. (2007) found that exposure to more than 2000 lx provided by daylight, in the early afternoon, increased alertness. Such findings imply that both physiological and psychological mechanisms are involved in determining alertness. Unravelling which, if either, of these routes is dominant, and when, is important because if the physiology is dominant, then a high light level is all that is required, but if the psychology is dominant, it may matter whether the light exposure is provided by electric lighting or by daylight.

This brings us to the third route whereby lighting conditions can affect work through mood and motivation. The visual system generates a model of the visual world and that may produce an emotional response. It is this emotional response, among many other factors, that may influence an individual's mood and motivation for work. The simplest way in which lighting may influence mood and motivation is when it generates a sense of visual discomfort. Lighting conditions in which achieving a high level of visual performance is difficult will be considered uncomfortable as will conditions in which the lighting leads to distraction from the task, as can occur when glare and flicker are present. But perception is much more sophisticated than just producing a feeling of visual discomfort. With or without visual discomfort, every lighting installation sends a message about the people who designed it, who bought it, who work under it, who maintain it and about the place it is located. Observers interpret the message according to the context in which it occurs and their own culture and expectations. The importance of this message is sometimes enough to override conditions that might be expected to cause discomfort, as shown by the fact that lighting conditions that would be considered extremely uncomfortable in an office are positively desired in a night club. According to what the message is, the observer's mood and motivation can be changed. Every lighting designer appreciates the importance of the message, but it is mainly in the context of retailing and entertainment that the message a lighting installation sends is given the importance that its potential to influence behaviour deserves (Custers et al., 2010).

While each of these routes has been discussed separately, it is important to appreciate that they can also interact. For example, someone who is asked to work while sleep-deprived will be fatigued. Similarly, anyone who attempts to work when their circadian timing system is disrupted will not perform well. Both these conditions will affect task performance through its cognitive component as well as its visual and motor components. Another example would be a situation where the lighting provides poor task visibility, so that visual performance is poor and the worker's mood is sour. There are multiple interactions of this type that can occur. To further complicate the picture, it is necessary to appreciate that while visual performance for a given task is determined by lighting conditions alone, a worker's mood and motivation can be influenced by a wide range of physical and social factors, lighting conditions being just one among many (CIBSE, 1999). It is this complex pattern of interacting effects that has made the study of the relationship between lighting and work so prolonged and difficult.

4.3 LIGHT, WORK AND THE VISUAL SYSTEM

The impact of lighting conditions on work performance that has been most extensively studied has been that based on the operation of the visual system. These studies can be conveniently classified into two broad groups: real-task studies and abstract studies. The differences between these two groups are essentially those of face validity and generality. The real-task studies involve taking a specific task that someone actually does and measuring the performance of the task under different lighting conditions, usually conditions that can be easily changed, such as the illuminance on the task, the spectral power distribution of the light source and the light distribution of the luminaires. These measurements are made either using a real task in the field or a simulated version of the task in a laboratory. Such studies have high face validity for the specific task, particularly when done in the field, but little generality. They lack generality because the results obtained strictly apply only to the task and the lighting installation used. Because other combinations of task and lighting system differ in the stimuli they present to the visual system and have different combinations of visual, cognitive and motor components, it is not possible to generalize results obtained on one task to any other. It could be argued that by undertaking enough real-task studies, an overall pattern could be detected that would allow generalization to occur but this seems a vain hope given the number of factors involved. Nonetheless, real-task studies have served to demonstrate that changing lighting conditions can alter task performance and, for the tasks studied, this gives a quantitative basis for deciding on appropriate lighting recommendations.

The abstract studies are characterized by the use of a task which is visually very simple and which no one has ever done for a living. The underlying aim of such studies is to achieve an understanding of how the performance of a visually simple task, with minimal cognitive and motor components, is influenced by lighting conditions. The outcome of such studies is usually a mathematical model that allows performance of the task to be predicted for lighting conditions not studied. By examining the effect of each of the meaningful stimuli a task presents to the visual system, it should be possible to predict the effects of lighting conditions on the visual performance of any task. Thus, the abstract studies follow the classical route to understanding through analysis followed by synthesis.

While these two approaches are clearly very different, they are interdependent. Without the results from the abstract studies, the results of the real-task studies are difficult to understand, a fact that makes generalization from them a matter of chance. On the other hand, if the abstract studies are to produce anything of value, they have to predict the results of real-task studies.

4.3.1 Field Studies

The first thing to say about field studies of the relationship between light and work is *caveat emptor*. Many claims have been made about the effect of lighting on worker productivity that are little more than assertions, without any of the details necessary to evaluate the claims made. However, there are a few field studies that deserve attention. Among the earliest were studies of such visual tasks as silk weaving (Elton, 1920), linen weaving (Weston, 1922) and typesetting by hand (Weston and Taylor, 1926), the last being a task that has now almost disappeared. All these tasks require the detection of small, low-contrast details so it is hardly surprising that they tend to confirm what is common experience and that lighting conditions can become inadequate for a task to be seen clearly, so increasing the illuminance leads to an improvement in performance. The illuminance at which this improvement ceases will depend on the nature of the task.

At about the same time as these early studies were being done, another series of studies were starting which have entered into folklore – the Hawthorne experiments (Snow, 1927; Roethlisberger and Dickson, 1939). Initially, these studies were concerned with the effects of lighting on productivity, although, for reasons that will become obvious, they later became more focused on the effects of payment systems, type of supervision, rest times and total hours of work. The Western Electric Company, based in Hawthorne, Chicago, manufactured electromechanical telephone apparatus. At the start of the studies, the company conducted three experiments on the effect of lighting on the output of a group of women who inspected parts, assembled relays or wound coils. In the first experiment, the illuminances on the tasks were varied in a series of steps, both up and down. Output in all three departments changed but showed no clear relationship to the illuminance. The second experiment used only the coil-winding department. The workers were split into two groups of the same level of experience. The control group was exposed to a relatively stable illuminance of 170–300 lx, while the test group was exposed to illuminances in the range 260–750 lx. As the illuminance of the test group was changed, the work output of both groups increased to a similar extent. The first and second experiments involved both electric lighting and daylight, the presence of daylight explaining some of the variability in illuminance. In the third experiment, daylight was eliminated. The same control group and test group that were used in the second experiment were used in the third experiment, but this time the control group worked under a constant illuminance of 110 lx, while the test group experienced illuminances starting at 110 lx and decreasing in steps of 11 lx. After the initial illuminance was set, both groups showed a slow but steady improvement in output. However, when the illuminance experienced by the test group reached 33 lx, the members of the test group protested that they could hardly see what they were doing and their output dropped.

From these studies, the experimenters concluded that lighting was only one, and apparently a minor factor among many that affected performance of the tasks, and that there was a whole area of what they called human relations waiting to be explored. Sometimes, this conclusion is distorted into a claim that these results imply that lighting has no effect on productivity and that the extent to which workers have control over their own activities, the relationships between workers and management and the consequences for the worker of their output are the only important factors. While there can be no disagreement with the statement that motivation and relationships are important, the assertion that lighting conditions can never affect work is nonsense. There is a continuum of performance associated with lighting conditions ranging from no light to plenty of light. In the absence of light, we can see nothing, no matter how large or high a luminance contrast the task has. Even when there is some light, the task details necessary to do the work may be below threshold. It is only when there is sufficient light to see the necessary details that performance becomes possible. As the amount of light on the task increases, it becomes possible to see more and more detail, so performance should increase until it becomes limited by some factor other than the visibility of the necessary details. There can be no doubt that lighting affects work; the problem is to identify the range of lighting conditions that allows an improvement in work output to occur. The operative word here is allowed. Lighting cannot produce work output. Only the worker can do that. What lighting can do is to make details easier to see and colours easier to discriminate without producing discomfort or distraction. The worker can then use this increased visibility to produce output if he/she is so motivated or is not limited by some other non-visual factor.

In the case of the Hawthorne experiment, the cause of the steady increase in output for both groups in the second experiment is generally ascribed to a change in motivation brought about by the greater self-determination of the workers (Landsberger, 1958; Urwick and Brech, 1965), although alternative explanations based on the frequent feedback of output, the consequences output had for pay and the nature of the supervision have also been proposed (Parsons, 1974; Diaper, 1990). Regardless of which, if any, of these explanations is correct, what has not been explained is why lighting conditions had no consistent affect. A plausible explanation for this lack of effect is that the visual component of the task was less than it appeared. What the workers were doing was winding coils on wooden spools. This was clearly a visual task but it was impossible to tell how difficult it was. The workers were well practiced at the task so the visual component may have been small. The impact of such practice can be seen when observing an experienced keyboard operator. Logically, it would seem that to press the appropriate key when typing would require the use of the visual system. However, an experienced keyboard operator rarely looks at the keyboard and can work well in near darkness. A similar situation may have applied to the coil winders. The results of the third experiment suggest that it was not until the illuminance fell to 33 lx that the visibility of the task began to limit the performance of the task.

While the initial Hawthorne studies failed to show any effects of lighting conditions on work output, there are other studies in the literature that do. Stenzel (1962) measured the output from a leather factory over a 4-year period, in the middle of which he introduced a change in lighting installation. The work involved punching out fault-free outer leathers from skins for handbags, purses, etc., using iron shapes and mallets. From 1957 to 1959, the lighting was provided by daylight, supplemented by local fluorescent lighting giving an illuminance of 350 lx. From 1959 to 1961, when the investigation stopped, the daylight was virtually eliminated and a uniform 1000 lx was provided by general fluorescent lighting. The average monthly performance for the 12 people who were present throughout the 4 years is shown in Figure 4.2. There is a statistically significant improvement in performance with the higher illuminance giving the better performance.

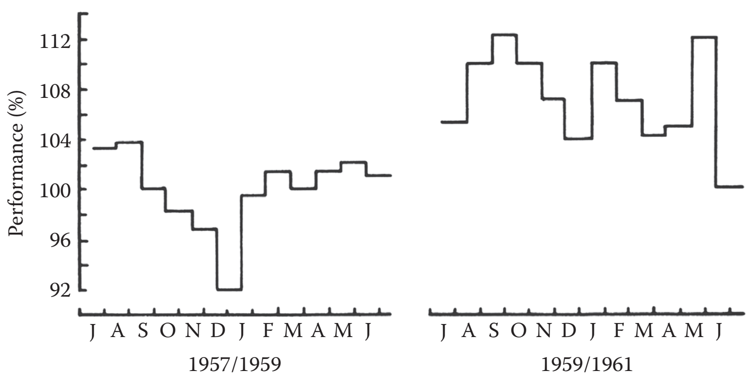

FIGURE 4.2 Mean monthly performance for cutting leather shapes for the years 1957–1959 and 1959–1961. Performance is normalized for the average performance over the years 1957–1959. (After Stenzel, A.G., *Lichttechnik*, 14, 16, 1962.)

Although this study was well controlled, it does illustrate two problems common in field studies. First, only two lighting conditions were used and those were widely different. Thus, the results do little more than demonstrate that changes in lighting can influence the performance of the task studied. Certainly, with only two illuminances, it is not possible to identify the optimum lighting conditions. Second, there is considerable uncertainty about the most important aspect of lighting for the change in performance because the change in lighting installation changed several different aspects of the lighting simultaneously. Specifically, the new lighting installation changed the illuminance on the task, the light spectrum and the light distribution. In these circumstances, to ascribe the changes in output to the difference in illuminance alone may be misleading.

Multiple changes made simultaneously are a problem that bedevils many field studies. Often, changes in lighting conditions are made at the same time as changes in decor, furnishings, equipment, working arrangements and people. If this is the situation, then ascribing any changes in output to lighting alone is also misleading. Another limiting feature of field studies is the variability in the nature of the work done and when it is done. Assembling different devices may call for different levels of visual performance, and assembling these devices in the early morning or late evening may introduce non-image-forming effects on top of any effects of lighting on visibility (Juslen et al., 2007a,b; Canazei et al., 2013).

The basic problem with field studies is the degree of experimental control required (Hartnett and Murrell, 1973). Ideally, the experimenter needs to be able to control the characteristics of the lighting installation, how it is used, the type of work done, the methods of payment and the people involved. It is only rarely that this degree of control is available but, when it is, believable field studies are possible. For example, Buchanan et al. (1991) measured the effect of increasing the illuminance in the pharmacists' working area on the dispensing error rate in a high-volume outpatient pharmacy. Based on an examination of 10,888 prescriptions, they found that increasing the illuminance from 485 to 1,570 lx leads to a statistically significant reduction in error rate from 3.9% of prescriptions filled to 2.6%.

It can be concluded that worthwhile field studies are possible but not probable. All field studies should be carefully reviewed to establish the extent to which the conclusions are justified. If insufficient information is given about the conditions studied, the work done, the way the data were collected and the nature of the statistical analysis, then it is safer to consider the conclusions as assertions rather than statements of fact, no matter how much they conform to preconceptions.

4.3.2 Simulated Work

The lack of control possible in many field situations initially turned many experimenters interested in the relationship between lighting and work back to the laboratory, where tasks simulating real-life tasks could be done under controlled conditions. Of course, this rather undermines the face validity of the task because it is now being done in a different context, so people may behave in a different way. Nonetheless, as long as the aim of the study is to determine the effect of different lighting conditions on the performance of the task through changes in task visibility, the gain in sensitivity from having good experimental control is usually worth the decrease in face validity.

There are a number of simulated task studies in the literature. Lion et al. (1968) examined the effect of using incandescent and fluorescent lighting on the inspection of plastic discs or buttons on a conveyor belt. The subject had to remove all the discs that had a broken rather than a complete loop marked on them and all the buttons with off-centre holes. The two forms of lighting provided the same illuminance on the conveyor belt (320 lx). Significantly better inspection performance was found when sorting the discs with broken loops under the extended fluorescent light source than under the incandescent point light source, but no significant effects of lighting were found for the buttonhole sorting. The probable reason for this difference between the two tasks is their visual difficulty and hence their relative sensitivity to lighting conditions. These results also serve to demonstrate the difficulty of generalizing from a specific task. Both these tasks could be regarded as sorting tasks, but the fact that the two tasks show different effects of lighting conditions means that the results cannot be applied to sorting tasks in general.

Other simulated work studies have been done by Stenzel and Sommer (1969) who examined sorting screws of different sizes and crocheting stoles; Smith (1976) who studied threading a needle; Bennett et al. (1977) who also studied needle probing as well as micrometer reading, map reading, pencil note reading, drafting, vernier caliper measurement, cutting and thread counting over a range of illuminances from 10 to 5000 lx; and McGuiness and Boyce (1984) who examined kitchen work. Most of these tasks showed an improvement in performance with higher illuminances, although the amount of improvement varied for different tasks. This should not be surprising because these studies are essentially about task performance rather than visual performance, so in addition to the differences in the stimuli the tasks present to the visual system, the tasks also differ in their cognitive and motor components. This is most evident in two studies by Smith and Rea (1978, 1982). In the Smith and Rea (1978) study, a small number of subjects proofread texts for misspelled words. Measurements of the time taken to proofread a passage and the percentage of errors found were taken at 4 different illuminances ranging from 10 to 4885 lx. Figure 4.3a shows the effect of increasing illuminance, which is to decrease the time taken and increase the percentage of errors found (hits). In the Smith and Rea (1982) study, the same apparatus was used, as was the same range of illuminances, but this time the subjects were asked to read a text and then answer questions about their comprehension of the text. There was little change in either speed or level of comprehension with increasing illuminance (Figure 4.3b). Reading for comprehension has a much larger cognitive component than proofreading.

Simulated work studies are undertaken where the need is to study the effect of lighting on a specific task. They certainly allow for more precise experimental control than is usually possible in the field, but they are inevitably limited in that the results are applicable to the specific task and cannot be generalized to other tasks. To use a metaphor, on the road to a general understanding of the relationship between light and work, simulated work tasks are a dead end. There is no reason to go there unless you have business there.

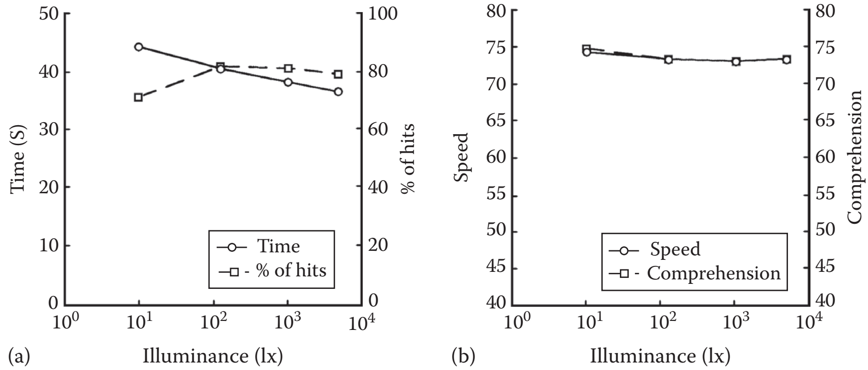

FIGURE 4.3 Performance on two types of reading task. For both tasks, the printing was of good quality on white paper: (a) time taken to proofread a passage and percentage of hits, that is, errors detected, plotted against illuminance and (b) speed and level of comprehension plotted against illuminance. (After Smith, S.W. and Rea, M.S., *J. Illum. Eng. Soc.*, 8, 47, 1978; Smith, S.W. and Rea, M.S., *J. Illum. Eng. Soc.*, 12, 29, 1982.)

4.3.3 Analytical Methods

One of the first attempts to produce a general model of the effects of lighting conditions on work was made by Beutell (1934). The basis of his method was first to define a standard task. The effect of lighting on this standard task could then be thoroughly investigated and the illuminance for any desired level of performance identified. Then the illuminance for any other task could be obtained by introducing a series of multiplying factors that allowed for differences between the task of interest and the standard task. The multiplying factors would be related to the visual size and luminance contrast of the critical detail of the task, any relative movement between the observer and the task and the degree of emphasis to be given to the task in its setting.

Beutell's suggestion was exploited by Weston (1935, 1945), who developed it into a widely used method of investigating the effects of lighting on work. What Weston did was to devise a very simple task in which the critical detail was easy to identify and measure. This task is usually known as the Landolt ring chart, being based on the Landolt ring used in the testing of visual acuity. Figure 4.4 shows an example of a Landolt ring chart. It consists of a series of Landolt rings, with the gap in the ring being orientated in one of the four cardinal directions of the compass. The critical detail of the Landolt ring is the gap. The size of the critical detail is the angular size of the gap and the critical contrast is the luminance contrast of the ring against its background. A practical advantage of the Landolt ring chart as a standard task is that it can be reproduced in large numbers, in many different media, and the critical size and contrast can easily be changed.

When doing the Landolt ring chart task, subjects are asked to read through the chart and mark, in some way, all the rings that have a gap orientated in a specified direction. The time taken to do this and the number of errors made under different lighting conditions are measured. These measures are then combined to form

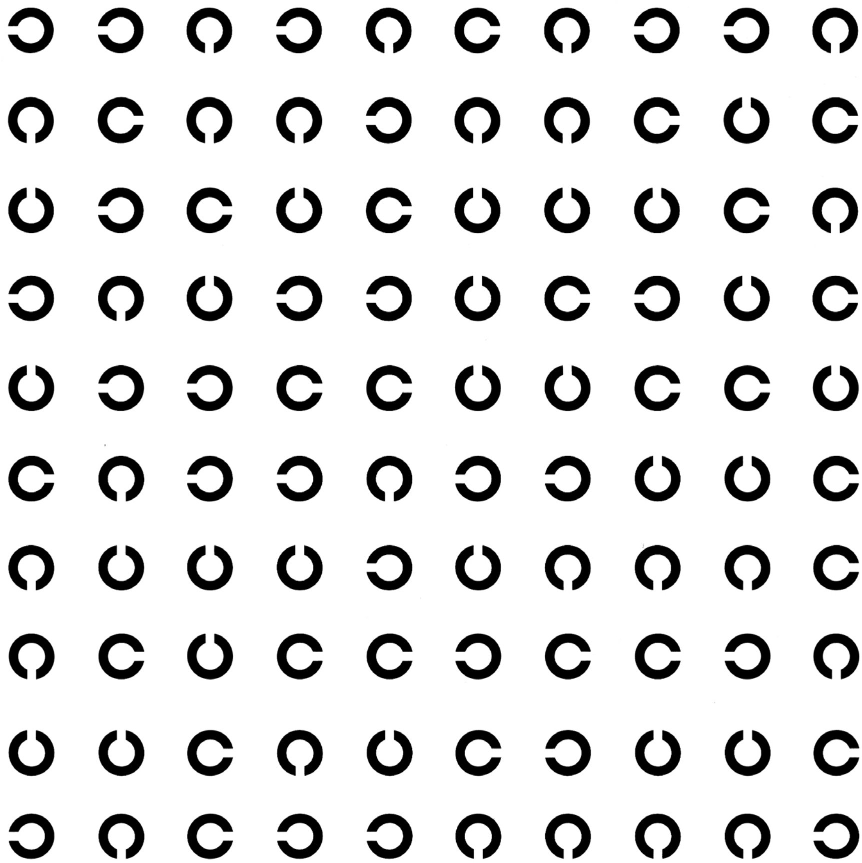

FIGURE 4.4 A Landolt ring chart.

measures of speed and accuracy of work. Speed is given by the number of rings correctly marked divided by the total time taken, the total time taken being reduced by subtracting the time taken to mark the same number of rings with a gap in the specified direction when they were marked with red ink. The subtraction of the time taken to mark the Landolt rings identified with red ink is an attempt to minimize the contribution of the cognitive and motor components of the task and hence to obtain a measure of visual performance rather than task performance. The rationale behind this is that by marking the rings that need to be identified with red ink, the visual component is minimized, so then the time taken is primarily determined by the cognitive and motor components of the task. Accuracy is given by the number of rings correctly marked divided by the total number of rings that could have been marked. Speed and accuracy are then multiplied to form what is called the performance score.

Figure 4.5 shows the results obtained by Weston (1945) in his second study. There are a number of conclusions that can be drawn from these results. First, the effect of increasing illuminance follows a law of diminishing returns, that is, that equal increments in illuminance lead to smaller and smaller changes in performance until

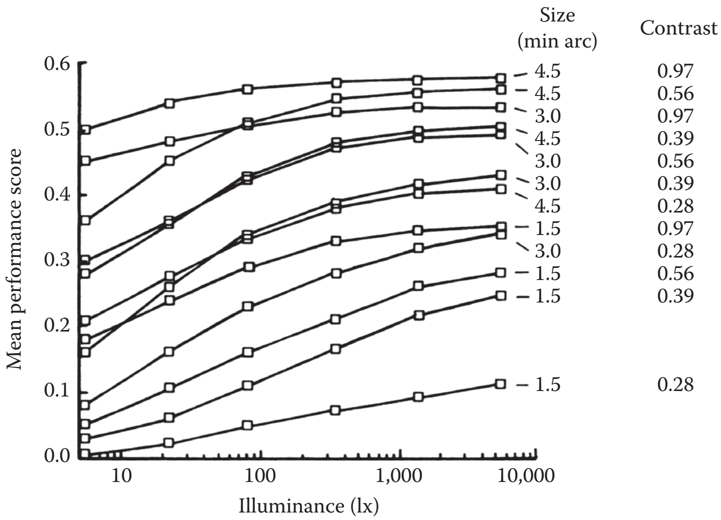

FIGURE 4.5 Mean performance scores for Landolt ring charts of different critical size and contrast, plotted against illuminance. (After Weston, H.C., The Relation between Illumination and Visual Efficiency: *The Effect of Brightness Contrast*, Industrial Health Research Board Report 87, HMSO, London, U.K., 1945.)

saturation occurs. Second, the point where saturation occurs is different for different sizes and luminance contrasts of critical detail, saturation occurring at lower illuminances for large-size, high-contrast tasks than for small-size, low-contrast tasks. Third, larger improvements in visual performance can be achieved by changing the task, that is, changing either the size or contrast of the critical detail, than by increasing the illuminance, at least over any illuminance range of practical interest. Fourth, it is not possible to make a visually difficult task, that is, small size and low luminance contrast, reach the same level of performance as a visually easy task simply by increasing the illuminance. Although these conclusions have been derived from Weston (1945), they have been confirmed many times since, using a number of different visual tasks (Khek and Krivohlavy, 1967; Boyce, 1973; Smith and Rea, 1978, 1982, 1987; Rea, 1981).

This general understanding about the relationship between lighting conditions and work demonstrates the value of an analytical approach based on the concept of critical detail. This observation is reinforced by Boyce (1974). In this study, subjects worked at a ring chart in two forms, one complex and one simple (see Figure 4.6). The visual size and luminance contrast of the gap in both simple and complex rings are the same, but the complexity of the task, in terms of the number of alternative locations of the critical detail, is much greater for the complex ring than for the simple ring. The question of interest is how does a change in illuminance affect the performance on the simple and complex rings. The results showed, as expected, that the complex ring chart took significantly longer than the simple ring chart to search but the change in performance with illuminances was similar for both simple and complex rings. In fact, the time taken to do the complex ring task at each illuminance was a constant multiple of the time taken for the simple ring task at the same illuminance. This result

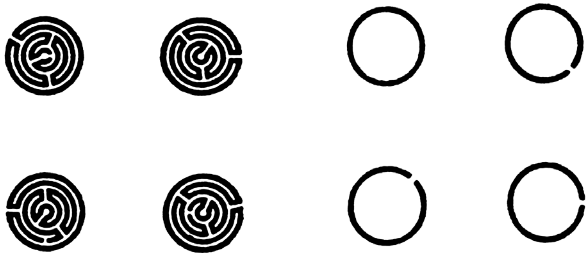

FIGURE 4.6 Complex and simple Landolt rings.

suggests that the visual difficulty of the task was adequately described by the size and contrast of the critical detail, that is, the size and contrast of the gap being sought in both forms of ring. The complex rings were not more visually difficult, because the gap size and contrast were identical to the simple ring, but they took longer to do because there were more possible locations of the gap. The effect of illuminance was determined by the critical detail.

The analytical approach adopted by Weston has served to demonstrate the general form of the relationship between lighting conditions, task characteristics and visual performance. It has also suggested how the visual difficulty of a task might be quantified and, hence, how the effect of lighting on the performance of the visual component of the task might be determined. However, as used by Weston, the results do have some limitations. Rea (1987) reviewed Weston's studies of 1935 and 1945 and observed that the trends in performance scores with illuminance for Landolt rings of the same visual size and similar luminance contrast were not consistent between the two studies. Rea (1987) also objected to the performance score metric. Specifically, he objected to the fact that the number of correct rejections, that is, the number of Landolt rings examined and correctly rejected as not having a gap in the specified direction, was ignored. Without considering the number of correct rejections, the measures of speed and accuracy must be imprecise. There is also a more general objection to the performance score metric. While both speed and accuracy are important aspects of task performance, it is better to treat them as separate but related measures of performance rather than to multiply them together, as is done in the Weston's performance score metric. The ideal approach would be to consider the effect of lighting on speed at a constant level of accuracy or accuracy at a constant level of speed. Unfortunately, the multiplication of speed and accuracy to obtain a single-number measure of task performance is common (Muck and Bodmann, 1961; Waters and Loe, 1973; Smith and Rea, 1978, 1979), but it is nonetheless arbitrary and serves to hide the effect of the experimental conditions on two rather different aspects of task performance. For all these reasons, Weston's results should be considered as indicative of general trends but should not be used as a basis for quantitative models of visual performance.

4.3.4 Visibility Approach

At the same time as the analytical approach was being developed in the United Kingdom, a rather different approach was emerging in the United States: the visibility approach. The concept behind the visibility approach is that the ease of seeing a task, such as a printed page, can be quantified by the separations of the stimuli the task presents to the visual system from their threshold values. The further the task's characteristics are removed from the threshold surface, the greater is the visibility of the task. It is then assumed that the visibility of the task is consistently related to task performance. The visibility approach was developed over many years, initially by Luckiesh and Moss (1937) and ultimately by Blackwell (1959) (see also CIE 1972, 1981), based on his extensive measurements of threshold contrast at different luminances (Blackwell, 1946; Blackwell and Blackwell, 1980). The metric of task visibility was visibility level, this being defined as

$$\text{Visibility level} = \frac{\text{Equivalent contrast}}{\text{Threshold contrast}}$$

Threshold contrast was defined as the luminance contrast of the visibility reference task, namely, detecting the presence of a 4 min arc diameter luminous disc presented against a uniform luminance field for 0.2 s. Equivalent contrast was the luminance contrast of the visibility reference task that is matched in visibility to the task of interest. Blackwell developed an instrument, called a visibility metre, to measure equivalent contrast, as well as multiplying factors to correct for departures in the viewing conditions of the task of interest from those used in the visibility reference task. He then made visibility level measurements for the stimuli used in other visual performance studies. Initially, these measurements led to the belief that there was a universal relationship between visibility level and visual performance. However, as more data on more tasks were collected, it became obvious that this was not true. It was concluded that the missing factors were the extent of search and scan of the visual field and the need to gather information off-axis. This led to the development of another standard task called the visual performance reference task. This consisted of five, 4 min arc Landolt rings, one in a central position and the other four at the four cardinal points of the compass, equidistant from the centre. By altering the luminance of the Landolt rings or the luminance of the background, the visibility level of the rings could be changed. By altering the presentation time or the separation of the central and peripheral rings, the difficulty of the task could be altered. Using the understanding gained from the visual performance reference task, a model was developed to predict the effect of lighting conditions on visual performance for a wide range of tasks (CIE, 1981). The model consisted of two sets of transfer functions operating in series. The first was concerned with how the lighting conditions affected the visibility level. The second was concerned with how the visibility level influenced visual performance. The model had three components linked to visibility level. These three components were related to extracting information from the details of the task, the stability of eye fixation and the precision of eye movements. The model could be made to fit independently obtained sets of experimental results but only by varying the weighting of the four components. As more data sets were examined, the number of correction factors that had to be introduced to make the model fit increased to such an extent that the model lost all credibility.

Although the visibility approach is rarely mentioned today, it should be appreciated that there is nothing inherently wrong with the concept of visibility level. The extent to which the stimuli a task presents to the visual system are above threshold is a useful way to quantify how well those details can be seen. Indeed, it has been used for this purpose in other fields of lighting, such as road lighting (Lipinski and Shelby, 1993). The problem with the concept of visibility level is the tendency for people to assume that equal visibility levels correspond to equal levels of task performance. This is not the case. Different tasks show different relationships between task performance and visibility level depending on the nature of the task (Clear and Berman, 1990; Bailey et al., 1993). The error in the visibility approach developed by Blackwell was to assume that something as complex as the suprathreshold performance of tasks with different visual and nonvisual components, occurring on- and off-axis, could be predicted from something as simple as an on-axis threshold measurement. In a sense, the visibility approach was simply a bridge too far.

4.3.5 Relative Visual Performance Model

After the collapse of the visibility approach as a method for predicting the effect of lighting conditions on visual performance, the time was right for a simpler but more rigorous approach. This need was met by the development of the relative visual performance (RVP) model. The principle adopted in the development of the RVP model was to establish a quantitative link between the physical characteristics of the task and the performance of the visual component of the task. The visibility level of the task was considered to be an unnecessary intervening variable. The visual characteristics of the task would be defined by quantities that could be directly measured.

The origin of the RVP model lies in a study of the effect of luminance contrast on performance of the numerical verification task (Rea, 1981). In this task, two printed pages, the reference page and the response page, each containing a column of 20, five-digit numbers are used. The five-digit numbers on the reference page were random numbers. The corresponding numbers on the response page were the same except that some of the five-digit numbers had one digit different (Figure 4.7). The mean frequency of such discrepancies was three per page. Data were collected for a constant illuminance on the printed pages of 278 lx and for a wide range of luminance contrasts for the reference page. Luminance contrast was varied by changing the reflectance of the ink used to print the numbers; by making the ink either specular or matte; by changing the geometry between the luminaire providing the illuminance, the numerical verification task and the observer; and by varying the percentage of vertical polarization in the light incident on the numerical verification task. Luminance contrast was defined as

$$C = \frac{|L_t - L_b|}{L_b}$$

where

C is the luminance contrast
L_b is the luminance of the background (cd/m^2)
L_t is the luminance of the detail (cd/m^2)

58313	58313
51424	51424
26538	26538
10508	10508
35148	35148
53427	53427
99147	99147
54483	54483
39154	39155
39417	39417
52807	52807
55394	55394
32393	32393
83118	83118
31510	31510
53009	53009
01632	01632
29394	29394
49619	49619
54101	54101

FIGURE 4.7 The numerical verification task.

The response page was printed in matte ink on matte paper in a high luminance contrast. The visual size of the numbers was held constant by using the same font and point size for the printing and by controlling the location of the subject's head with a chin rest. Data were collected on the time taken to compare the two columns of figures, the number of discrepancies missed (misses) and the number of identical five-digit numbers marked as discrepancies (false positives). Figure 4.8 shows the change in the mean time taken, misses and false positives for decreasing luminance contrast. It is evident that for a wide range of luminance contrasts, there is very little change in any of the performance measures. However, as luminance contrast drops below about 0.4, the time taken starts to increase, an increase that accelerates as luminance contrast decreases further. A similar pattern is seen for the misses and false-positive data. These data illustrate that both the speed

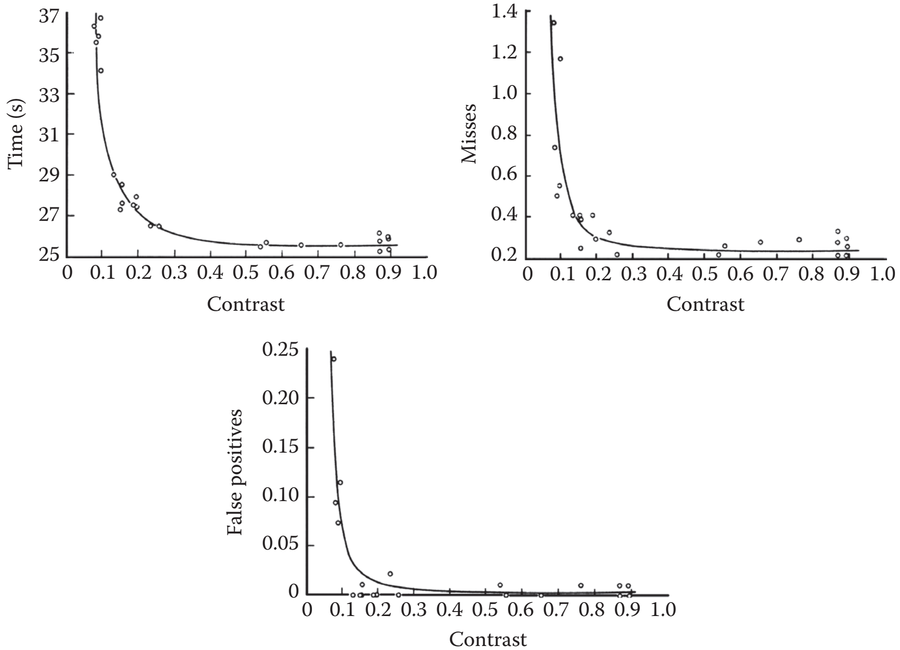

FIGURE 4.8 The mean time taken, number of misses and number of false positives for the numerical verification task, plotted against luminance contrast. (After Rea, M.S., *J. Illum. Eng. Soc.*, 10, 164, 1981.)

and accuracy of performance deteriorate with reduced visibility in a non-linear manner. They also demonstrate that luminance contrast is a major determinant of task performance, no matter how that luminance contrast is achieved.

The first complete version of the RVP model (Rea, 1986) was derived from data collected from people doing the numerical verification task using the same experimental materials, experimental room and procedures as in the earlier study (Rea, 1981). Data were collected for a range of illuminances from 50 to 700 lx (giving a range of background luminances from 12 to 169 cd/m^2) and a range of luminance contrasts from 0.092 to 0.894, luminance contrast being defined as in the 1981 study. The data on time taken to compare a set of 20, five-digit numbers, the number of misses and false positives were very similar to those obtained in the earlier study (Rea, 1981) and by others using the numerical verification task (Slater et al., 1983). In developing the RVP model, Rea decided to use only the time taken data. This decision was taken for a number of reasons, the most important being that the number of misses and false positives were small and subject to random fluctuations, factors that made misses and false positives less reliable measures of performance than time taken and because the variations of all three measures with luminance contrast were very similar. Figure 4.9 shows the change in the reciprocal of time taken plotted against luminance contrast at each of the background luminances. Figure 4.9 shows the compressive function with luminance contrast that would be expected from the results in Figure 4.8. There are two effects of

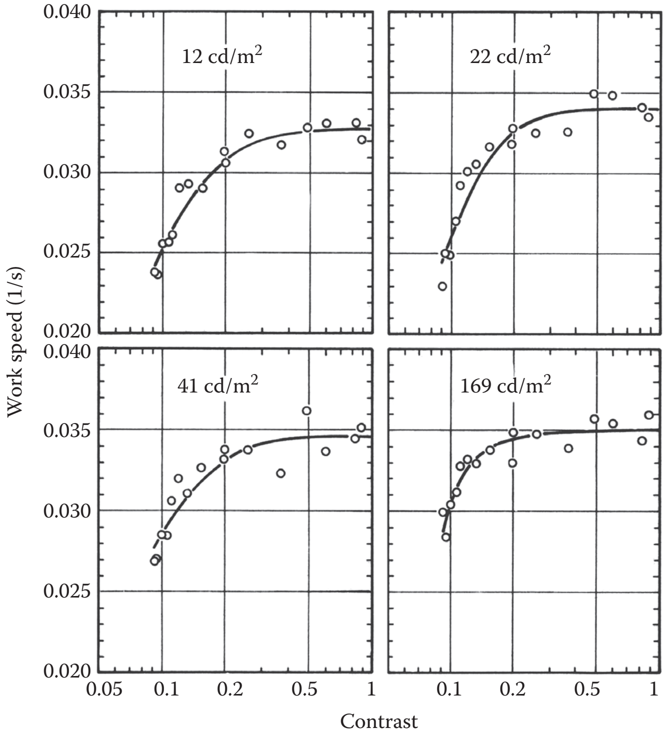

FIGURE 4.9 Mean work speed, expressed as the reciprocal of time taken to perform the numerical verification task, plotted against luminance contrast, for four background luminances. (After Rea, M.S., *J. Illum. Eng. Soc.*, 15, 41, 1986.)

increasing luminance that should be noted. The first is that, at the same luminance contrast, even very high luminance contrast, performance is better at higher luminances. The second is that performance tends to saturate at lower luminance contrasts for higher luminances.

The time taken to compare the reference and response pages used as the basis of Figure 4.9 is a measure of task performance, in that it includes both visual and non-visual components. To produce a time measure that could reasonably be called a measure of visual performance, Rea subtracted two elements of time from the total time taken. The first was an estimate of the time taken to make a mark against any response page number that contained a discrepancy. The second was the time taken to read the numbers in the response list. The remaining time was then the time taken to read the numbers in the reference list. It is the reciprocal of this time that was taken as a measure of visual performance from which the RVP model was developed. Figure 4.10 shows the form of the RVP model plotted against background luminance of the range 12–169 cd/m^2 and luminance contrast over a range 0.08–1.0. It should be noted that the vertical axis is a relative measure (RVP) calculated from the reciprocal of the time taken to read the reference page, normalized to a value of 1.0 at a background luminance of 169 cd/m^2 and a luminance contrast of 1.0. Memorably,

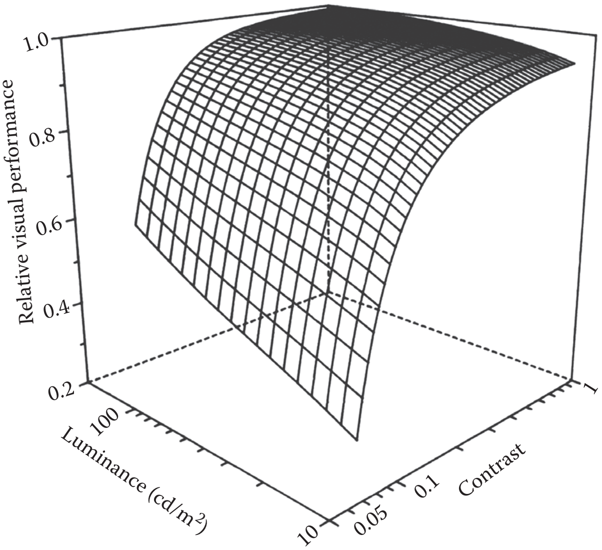

FIGURE 4.10 The RVP model of visual performance, based on the time taken to read the reference page of the numerical verification task. (After Rea, M.S., *J. Illum. Eng. Soc.*, 15, 41, 1986.)

the shape of this model has been described as the plateau and escarpment of visual performance (Boyce and Rea, 1987), the point being that over a wide range of task and lighting variables, the change in RVP is slight but at some point it will start to deteriorate rapidly. The evolutionary advantage of having a visual system that can cope with a wide range of visual conditions with little change in speed of response is obvious.

The second form of the RVP model (Rea and Ouellette, 1988) was developed using a very different approach. Whereas in the first approach, a task with some similarity to tasks actually done by someone, the numerical verification task, was used and the performance measure later adjusted to make it a measure of visual performance; in the second approach, the task used was one that could be taken as a direct measure of the speed of visual performance. Specifically, the performance measure was simply the reaction time to the onset of a square stimulus. Detecting the presence of something as against nothing is about the simplest visual task possible. There is very little cognitive component, and as the only motor component is to release a button when the stimulus is presented, the motor component is slight as well. Reaction time measurements were taken for stimuli with a wide range of luminance contrasts, both positive and negative, angular sizes and adaptation luminances. Luminance contrast was defined as before. Visual size was defined as the solid angle subtended at the eye by the stimulus. An equation of the same form as that used to fit the reciprocal of time taken to do the numerical verification task was applied to the reciprocal of reaction time and fitted the data well. To convert the reaction times into a relative measure, the differences in reaction time between each stimulus condition and the shortest reaction time (obtained for the largest size, highest contrast and highest adaptation luminance) were calculated. This measure shows the expected increase in reaction time following reductions in visual size, luminance contrast or amount of light entering the eye.

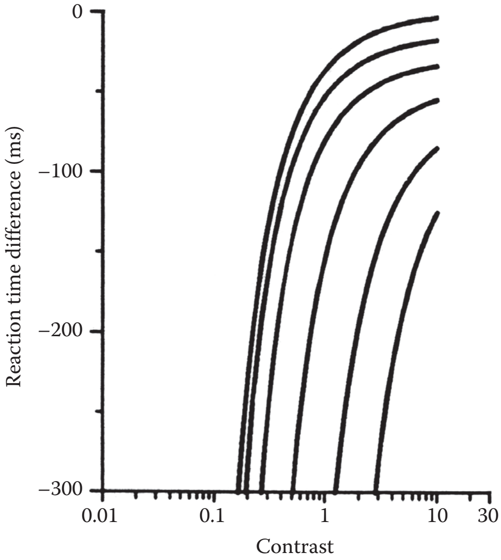

FIGURE 4.11 Fitted curves showing the difference in reaction time to the onset of a target subtending 2 μsr at the eye, plotted against luminance contrast. Each curve is for a different retinal illumination. From left to right, the retinal illuminations are 801, 160, 31, 6.3, 1.6 and 0.63 trolands. (After Rea, M.S. and Ouellette, M.J., *Lighting Res. Technol.*, 20, 139, 1988.)

Figure 4.11 shows the curves fitted to these differences in reaction time, plotted against luminance contrast, for different amounts of light entering the eye.

At this point, there were two alternative forms of the RVP model, one based on the time taken to read the reference page of the numerical verification task (Rea, 1986) and the other based on the difference in reaction time for detecting the presence of a target (Rea and Ouellette, 1988). Fortunately for simplicity, Rea and Ouellette (1991) were able to develop a method for converting the reaction time difference into units of RVP. They did this by identifying a common set of stimulus conditions and then developing a linear transformation between the two measures. What this means is that the differences in reaction times can be expressed in terms of RVP. Figure 4.12 shows the RVP values derived from the reaction time measurements plotted against luminance contrast and retinal illumination for four different visual sizes of the detection target. The average visual size of the digits used in the numerical verification task is 4.8 μsr, so this part of Figure 4.12 is comparable with Figure 4.10. The similarity between the two figures is obvious.

This has been a complicated discussion, but it is worthwhile because it is important to understand the development of the RVP model. The RVP model represents the most complete method currently available for predicting the effect of both task and lighting variables on visual performance. It has been very carefully developed, using rigorous methodology and careful reporting. What needs to be considered now is how well the RVP model predicts the results of independently collected data.

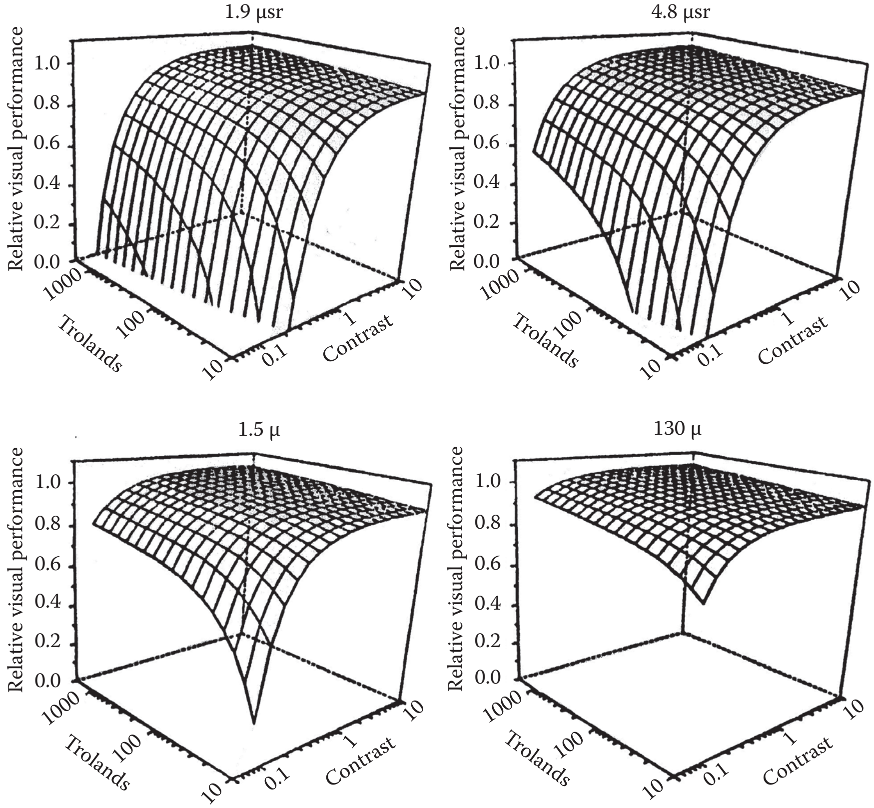

FIGURE 4.12 The RVP model of visual performance based on reaction time data. Each graph shows the RVP value plotted against luminance contrast and retinal illumination (in Trolands), for a fixed target size (in μsr). (After Rea, M.S. and Ouellette, M.J., *Lighting Res. Technol.*, 23, 135, 1991.)

There are two answers to this question. The first comes from the study of Bailey et al. (1993). In this study, the speed of reading unrelated words was measured, when the words were presented in sizes ranging from 2 to 20 point print, at three different luminance contrasts (0.29, 0.78 and 0.985) and over a range of background luminances from 11 to 5480 cd/m^2. The reading speed was calculated from the time taken to read each row of words and the number of words in each row. The time taken to read each row was measured from a recording of the eye movements made during the reading. Figure 4.13 shows the measured reading speeds plotted against letter size. The plateau and escarpment shape of visual performance is again evident. Bailey et al. (1993) then applied the formula used by Rea to fit their reaction time data (Rea and Ouellette, 1988) to the stimulus conditions in their experiment to predict the reaction times for each combination of background luminance, letter size and luminance contrast. Then reading speed was calculated as a linear function of reaction time, with two free variables. The resulting fit of the predicted reading speed to the measured reading speeds was good for letter sizes of 5 point and above, for all luminance contrasts

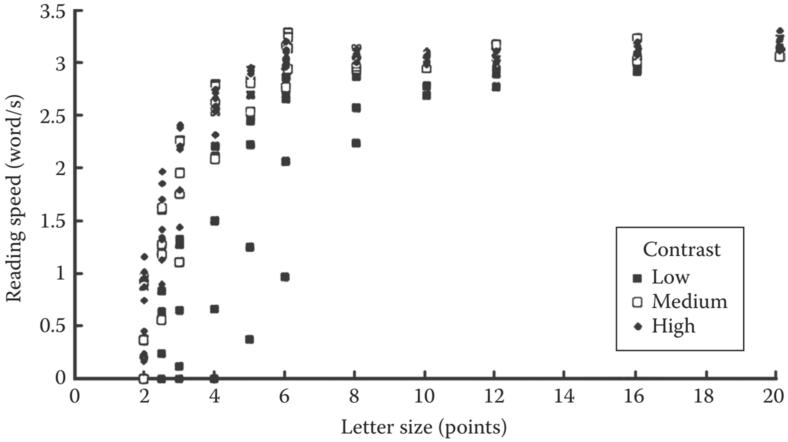

FIGURE 4.13 Mean reading speed measured in word per Second plotted against letter size in points for three different luminance contrasts. (After Bailey et al., *J. Illum. Eng. Soc.*, 22, 102, 1993.)

and background luminances. However, as letter sizes decreased below 5 point, the predictions became increasingly in error. This is not unreasonable, for two reasons. First, the data on which the RVP model is based did not cover stimulus sizes equivalent to 5-point print and smaller, so such smaller letter sizes were outside the range of the model. Second, it is likely that as letter size decreases, the ability to read the word becomes limited by the ability to resolve the detail of the letter, regardless of luminance contrast. The fact that the basic formula used in the RVP model can be applied to independently collected data on a reading task and give accurate predictions of reading speed over a range of print sizes of practical interest is encouraging as evidence that the underlying concept is correct. However, it is not conclusive proof of the validity of the RVP model because of the two free parameters that were adjusted to maximize the fit.

The second answer comes from the work of Eklund et al. (2001). They measured the effect of different lighting and print conditions on the sustained performance of a repetitive, self-paced, data-entry task. Twenty-four people worked for almost 4 h at a data-entry task in one of three identical, private, windowless offices. All three offices were lit by similar fluorescent, parabolic lighting systems. The installations were fitted with dimming systems to allow the illuminance on the work to be systematically changed to four levels (29, 103, 308 and 1035 lx). During the 4 h of work, the subject entered sets of five, 10-symbol, alphanumeric codes, the sets being printed in a cyclical series of print sizes (6, 8, 12 and 16 point) and luminance contrasts (0.10, 0.22, 0.47 and 0.93). In total, task performance measurements were taken for 60 combinations of illuminance, print size and luminance contrast. The task performance measurements taken were the times taken to enter a block of 50 alphanumeric symbols correctly. Any errors made in data entry were detected by the software running the experiment and had to be corrected before proceeding, thereby increasing the time taken. The result of this procedure is to fix the accuracy of performance at 100%. Figure 4.14 shows the mean work speed, derived from the reciprocals of the

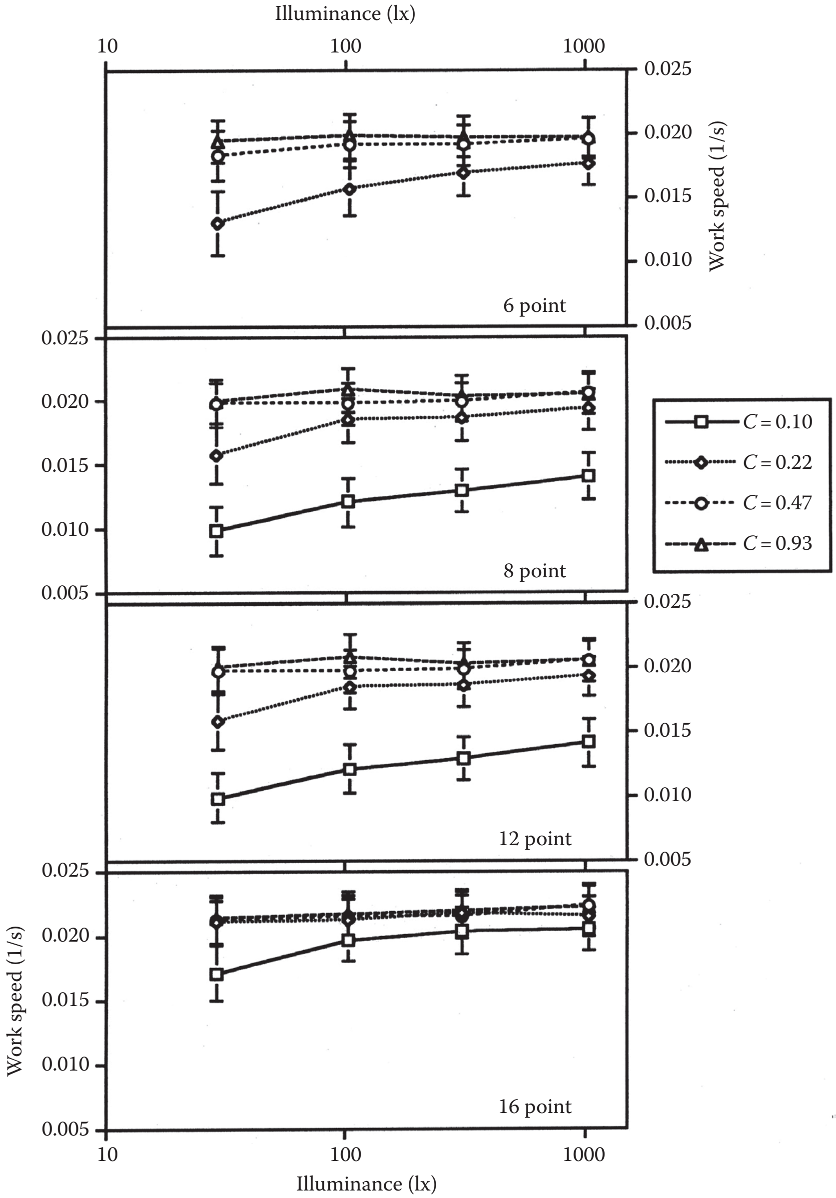

FIGURE 4.14 Mean work speeds for the data-entry task for four print sizes. Each graph shows the mean work speed plotted against illuminance (lx) for four luminance contrasts. The error bars indicate 95% confidence intervals. Note that the plot for the 6-point print contains data for only three luminance contrasts. Six-point print of luminance contrast 0.10 could not be read by a significant number of subjects at any of the illuminances used. (After Eklund, N.H. et al., *J. Illum. Eng. Soc.*, 29, 116, 2000.)

work times, plotted against illuminance, for each luminance contrast and print size. These data were used to test the precision of the RVP model based on the reaction time data given in Rea and Ouellette (1991). The mean inked areas of the letters and numbers printed in the different point sizes were measured as were the luminance contrasts and the background luminances. These values were then inserted into the RVP model to predict the RVP. The predicted RVP values were then normalized at the value found for the largest size (16 point), highest contrast (0.93) and highest illuminance (1035 lx). The measured mean work speeds on the data-entry task were also normalized for same conditions. Figure 4.15 shows the normalized predicted performance plotted against the normalized measured performance. It is clear that the RVP model fits the measured data well, although not perfectly.

These three comparisons serve to demonstrate the robustness and validity of the RVP model. The Eklund et al. (2001) study also removes some of the doubts about its utility. Some of these doubts have arisen from the conditions under which the reaction time data used to form the RVP model were collected. For example, the reaction time data were collected monocularly, using an artificial pupil, and with the subject's head at a fixed distance from the stimulus. Further, the only task was to detect the presence of a square target of a fixed size, which does not require resolution of detail. In the Eklund et al. (2001) experiment, the subject used natural pupils and could move closer or further from the data-entry material as they wished and they had to read alphanumeric characters. Other doubts have arisen because different letters and numbers of the same nominal print size vary in inked area. In the Eklund et al. (2001) experiment, the data-entry material was a random collection of letters and numbers of the same nominal size and hence a collection of letters and numbers that varied in inked area. The fact that the RVP model is consistent with the mean work

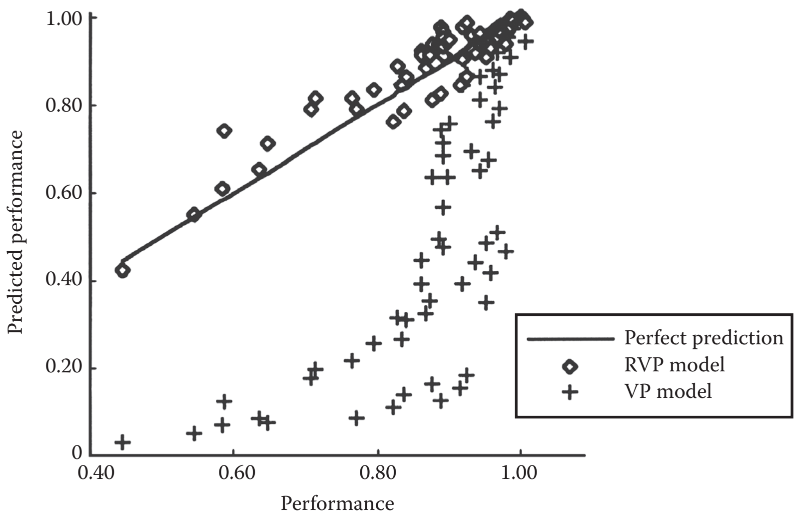

FIGURE 4.15 Normalized RVP values predicted by the RVP and VP models for the data-entry task plotted against the normalized measured mean work speeds. (After Eklund, N.H. et al., *J. Illum. Eng. Soc.*, 30, 126, 2001.)

speed measured over a 4 h work period in real-world conditions suggests that these doubts are unjustified. Over time, the variations in the stimuli presented to the visual system caused by different viewing distances and different inked areas average out and hence can be ignored.

4.3.6 Some Limitations

From the information presented earlier, it can be concluded that the RVP model represents the closing of the circle, from an abstract model of visual performance to the performance of a realistic task done under realistic conditions. This, in turn, suggests that the RVP model could be used to predict the change in visual performance for other tasks consequent upon changing either the lighting or the task. The existence of this possibility should not be taken to mean that the long study of the relationship between light and work is at an end. A more accurate understanding would be that the RVP model represents a concept that can be applied to a limited range of tasks. The tasks for which it is most suited are those that are dominated by the visual component; that do not require the use of peripheral vision to any great extent; that present stimuli to the visual system that can be completely characterized by their visual size, luminance contrast and background luminance only; and that have values for these variables that fall within the ranges used to develop the RVP model.

The limitation of a small nonvisual component is derived from the fact that RVP measures visual performance, not task performance. These two types of performances are only likely to coincide when the nonvisual components are relatively small or when parallel processing of information can occur, as seems likely to have happened in the data-entry task of Eklund et al. (2001). If the nonvisual component is large and parallel processing is not possible, then RVP predictions will overestimate the consequences of a change in visual conditions on task performance. What is needed to extend the use of the RVP model to tasks with significant nonvisual components is the development of a task analysis procedure that could be used to determine the relative impacts of the visual and nonvisual components on the performance of any task.

The limitation to tasks using only foveal vision occurs because the tasks used to derive the RVP model and the tasks used to validate it all let the participant know where to look to gain the necessary information. This is not true of all tasks. Specifically, tasks requiring extensive visual search to find the required information use peripheral vision and peripheral vision can be very different from foveal vision (see Chapter 2). However, it is important to appreciate that this caveat only applies to a true off-axis task. Where the task is a combination of off-axis detection and on-axis identification, particularly if the area to be searched is limited, RVP may well provide reasonable estimates of the effect of lighting conditions on performance. This is evident in the work of Bullough et al. (2012a) who showed that RVP could be consistently related to the time taken to identify the apparent direction of movement of black silhouettes of an adult and a child on a pedestrian crossing under different forms of lighting (see Figure 11.7).

The limitation to tasks with stimuli that can be completely characterized by the visual size, luminance contrast and background luminance is necessary because these are the factors built into the RVP model. Other aspects of visual stimuli that can be important are colour difference and retinal image quality. When applied to print, Smith and Rea (1978) and Colombo et al. (1987) have both shown that the effect of illuminance was much greater for fragmented print than for entire print. As for colour difference, O'Donell et al. (2011) have shown that having a coloured stimulus and a neutral background can sustain visual performance even when there is zero luminance contrast between the stimulus and the background. More exactly, the effect of such a colour difference on visual performance depends on the luminance contrast available and the hue and saturation of the colour. When the luminance contrast of the stimulus is less than 0.2, a saturated colour is required to maintain a high level of RVP, exactly how saturated depending on the specific colour. If the luminance contrast lies in the range 0.2–0.6, an excitation purity of only 10% is necessary to achieve a high level of RVP. When the luminance contrast is above 0.6, the presence of a colour difference is not necessary to achieve a high level of RVP.

Finally, it is worth noting that other models of visual performance have been constructed. One, called the VP model, is based on the data of Weston (1945). Adrian and Gibbons (1994) took these data and performed an extensive curve-fitting exercise to produce a quantitative model to predict the speed and accuracy of performance on the Landolt ring task from the measured visual size, luminance contrast and background luminance (CIE, 2002a). Unlike the RVP model, the VP model provides a poor fit to the independently collected task performance data of Eklund et al. (2001) (Figure 4.15).

Eklund et al. (2001) themselves performed a sophisticated curve-fitting procedure on their data to produce what they called the data-entry task performance model. There was a good fit between the predicted mean work times and the measured mean work times for the data-entry task. Clear and Berman (1990) had a more general aim in mind when they put forward a model of task performance in which performance is determined by the addition of two components, one visual that can be related to a visibility level–type metric and one nonvisual component that is independent of visibility level. They show that a model of this form can be made to fit the Rea (1986) numerical verification task performance data and can handle both speed and accuracy measures of task performance. A similar approach was used by Bailey et al. (1993) to fit their reading speed data, but in this case, the visibility level metric was based on visual size rather than luminance contrast. It is important to appreciate that these models are not models in the same sense as the RVP model. The difference is that the RVP model is a model of visual performance and all the measurements needed to make an RVP prediction can be obtained from physical measurements of visual size, luminance contrast and background luminance of a task. The task performance models are either applicable only to the specific task or require additional information before they can be used. Further, the necessary information cannot be obtained except by measurement of performance of the task, which raises the question as to why is it necessary to make a prediction of the effect of changes in the visual conditions on task performance, when the performance has to be measured directly before the prediction can be made. Really, the value of these models of task performance is the concepts they introduce. It may be that at some time in the future, there will be enough data collected for it to be possible to classify tasks according to the relative importance of their visual and nonvisual components and to use some of the task performance models. Until that glorious day arrives, the RVP model marks the quantitative frontier of the search for an understanding of the relationship between light and work done using the visual system.

4.4 LIGHT, WORK AND THE NON-IMAGE-FORMING SYSTEM

So far, this examination of the relationship between light and work has concentrated solely on the effect of lighting conditions operating through the visual system. The effects of lighting on task visibility and hence visual performance will be evident at all times, but as soon as the non-image-forming system is considered, when the work is done becomes important.

4.4.1 Light and Work at Night

Humans are diurnal mammals that are active during the day and sleep at night. People will experience difficulty in performing many sorts of task if they are asked to do it at a time when their circadian timing system is telling them to sleep. Figure 4.16 shows the percentage of errors made in reading gas metres at different times over 24 h. The increase in errors at night and around 14.00 h, called the post-lunch dip, is obvious (Minors and Waterhouse, 1981). Similar deteriorations in task performance at night have been shown for the frequency of falling asleep while driving, for the speed of joining threads in textile production, for train drivers missing warning signals and for the frequency of minor accidents in hospital (Folkard and Monk, 1979). At first, the finding that performance of many industrial tasks is worse during the night than during the day might be thought inconsistent

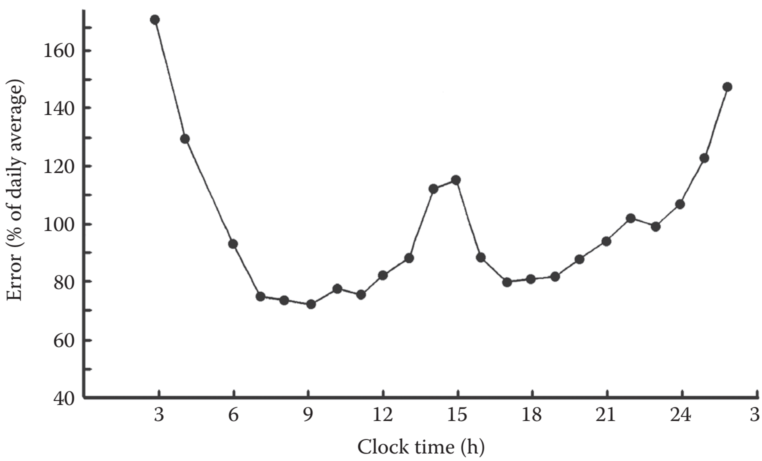

FIGURE 4.16 Variation in errors made in reading gas metres at different times over 24 h. (After Minors, D.S. and Waterhouse, J.M., *Circadian Rhythms and the Human*, Wright, Bristol, U.K., 1981.)

with the fact that illuminances at a level typically used in interiors at night can entrain the circadian timing system (see Section 3.4). There are two reasons why this is not enough to guarantee good task performance at night. The first is that the extent and speed of phase shifting is dependent on the pattern of how much light exposure occurs and when it occurs, over the whole 24 h. Exposure to daylight, as might occur on the journey to and from work and which gives a much higher retinal illumination than most interior lighting, will usually determine the phase of the circadian system and may stop the phase shift necessary to reset the circadian rhythm to what is needed for night-shift work. The second is that even with carefully controlled exposure to daylight, a 180° phase shift takes about 15 days (Monk et al., 1978). This implies that a rapidly rotating shift system that involves only two or three successive nights of work does not allow enough time for adaptation to occur. This is confirmed by Sack et al. (1992) who measured the melatonin concentrations of a group of workers over the 24 h immediately following the end of 3–5 days of continuous night shifts. Figure 4.17 shows the average melatonin concentration profile of the group of night-shift workers relative to that of a control group of dayworkers. There is evidence of partial adaptation occurring, the maximum melatonin concentration occurring about 19.00 h for the night workers rather than the 02.00 h for the dayworkers.

This pattern of slow adaptation suggests the possibility of using light exposure to systematically and more rapidly phase shift the circadian system to the required condition. Czeisler et al. (1990) have demonstrated that a pattern of exposure to light can be developed that will produce a marked phase shift to an adapted state in 4 days, even when the subjects are exposed to daylight on the journey home. This was achieved by exposure to an illuminance in the range 7,000–12,000 lx during the night shift from 00.15 to 07.45 h. Czeisler et al. (1990) also showed that as a result of this adaptation, the subjects had a greater feeling of alertness

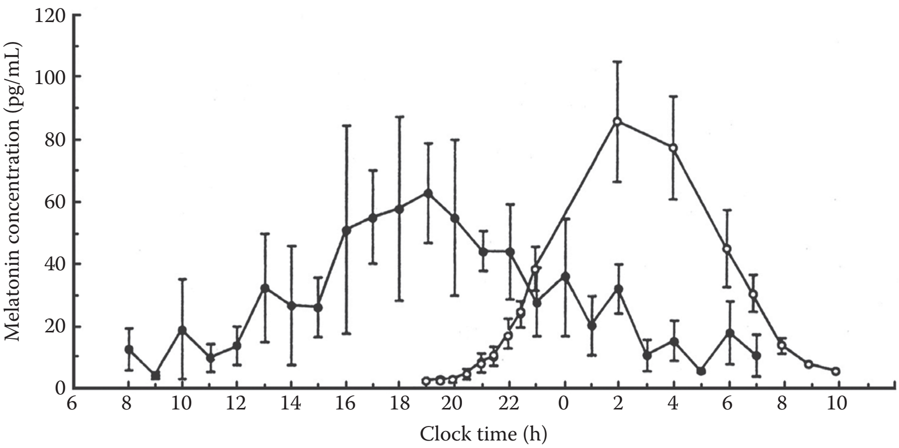

FIGURE 4.17 Average melatonin concentration plotted against clock time for a group of day-active people (open circles) and a group of night-active people (filled circles), after five successive night shifts. (After Sack, R.L. et al., *Sleep*, 15, 434, 1992.)

and achieved better performance on mental arithmetic during the night shift than a control group which showed no adaptation.

Eastman et al. (1994) performed a similar study on night-shift work, but in this case, the light exposure and the wearing of dark welder's goggles were combined in all possible ways. This meant that some participants were exposed to 5000 lx illumination at night but were free to travel home without wearing the goggles. Others were exposed to less than 500 lx at work but wore the dark welder's goggles during the journey home. Yet, others were exposed to 5000 lx at night and wore the welder's goggles on the journey home, while yet others were exposed to 500 lx but did not wear the goggles while travelling home. All the participants slept in darkened bedrooms receiving less than 500 lx in daytime. Receiving 5000 lx at night and wearing the goggles during the day gave the greatest phase shift, either factor alone gave some shift while neither rarely produced any phase shift. This result emphasizes two points. The first is that illuminances typical of conventional interior lighting can produce phase shifts (i.e. 500 lx during the night) provided exposure to daylight is limited. The second is that to guarantee a phase shift, it is necessary to control light exposure throughout the 24 h.

Both the aforementioned studies were conducted in laboratories to determine the practicality of using controlled light exposure to accelerate adaptation to a sudden shift in work time. One application where controlled light exposure has been of practical value is in spaceflight. A NASA space shuttle crew is required to start preparations for launch about 2 a.m. After launch, the crew is split into two teams, both of which work 12 h shifts. Crews on early shuttle flights complained of fragmented and disturbed sleep. In 1990, the conference room in the crew quarantine quarters was fitted with a luminous ceiling capable of producing about 10,000 lx. The crew entered the quarantine quarters one week before launch and went through a light exposure pattern of bright light and darkness designed to adapt them to their anticipated work schedule. The returning crew reported much better sleep patterns in flight. Melatonin samples indicated that adaptation had occurred (Czeisler et al., 1991). Reports of the application of light exposure to more mundane industrial activities are rare but one that is available suggests that providing bright light exposure to speed up adaptation has only limited value (Bjorvatn et al., 1999). The fact is that although it has been shown to be possible to rapidly and fully adapt to and from night shift using patterns of light exposure based on the phase response curve, and light–work–sleep schedules for adaptation to night-shift work have been published (Eastman, 1990), controlled light exposure as a means to adapt to night shift work has rarely been used in practice. Possible reasons for this lack of impact on lighting practice are the difficulty of ensuring compliance with the light exposure pattern throughout the 24 h in a conventional industrial context and the lack of demand for something better from night-shift workers, probably due to their low expectations. This may change if the compromise protocol suggested by Smith et al. (2009) is adopted. This uses exposure to short 15 min bursts of bright light (4100 lx) every hour at night to shift the time of maximum sleepiness to 10:00, that is, after the shift. This still requires care with light exposure over the 24 h as shown by the facts that sunglasses have to be worn when outside during the day and sleep has to be in a dark room, but benefits in terms of performance, fatigue and mood have been found.

Given that attempts to match the circadian timing system to night-shift work are rare, it is interesting to consider what the effects of misadaptation would be on task performance. The first thing to say is that the effect of trying to work in the circadian night can affect all types of task, not just visual tasks. This is because the circadian system affects the platform from which we operate and consequently affects all parts of the brain and body. Tilley et al. (1982) studied the sleep patterns and performance of shift workers operating a weekly, alternating, three-shift system. Workers doing night shift, who had to sleep during the day, had shorter duration sleep of degraded quality. As for performance, both simple reaction time and four-choice reaction time were longer during night shift relative to day and afternoon shift and tended to show a deterioration over the number of days on shift, probably because of the accumulation of sleep deficit caused by the inferior sleep duration and sleep quality during the day.

Fortunately, there is another way to improve task performance at night. It is well established that the onset of sleepiness and the deterioration of the performance are closely related to the increase in melatonin concentration. It is also well established that exposure to light can rapidly suppress melatonin. The interesting possibility is that exposure to bright light at night could lead to an improvement in performance of some tasks. There is some evidence to support this possibility. French et al. (1990) measured the performance of people on a battery of cognitive tests while working between 18:00 and 06:00 h and exposed to either 3000 or 100 lx illumination. Performance on six of the ten cognitive tasks done was improved by exposure to bright light, the biggest effect being on serial subtraction and addition. A similar pattern of results were obtained by Badia et al. (1991), with subjects working at night being exposed to alternating 90 min periods of bright (5,000–10,000 lx) and dim (50 lx) light. Of the six cognitive tasks measured, three showed significantly increased levels of performance during the bright light periods, although all tasks showed deterioration over the night. Boyce et al. (1997) showed a similar pattern for people working three successive nights under the same lighting installation. Out of seven tasks performed, two showed statistically significant improvements when the work was carried out under 2800 lx on the work surface from midnight to 08:00 h or from midnight to 02:30 with a steadily declining illuminance until 08:00 h. Work over the same time periods at a fixed 200 lx illuminance or with an increasing illuminance that only reached 2800 lx at 05.30 h produced lower levels of performance.

One common feature of these results is that some tasks are more sensitive to the effects of working at night than others. Studies of night-shift work have shown that the tasks most sensitive to work at night, and hence which benefit most from melatonin suppression, are of two types. One is cognitively complex requiring the mental manipulation of information, for example, analysing a complex logistics problem and finding an optimal solution (Boyce et al., 1997). The other is a vigilance task, where attention has to be paid to unchanging information in case something happens but it rarely does, for example, a security guard on a closed industrial site (Cajochen et al., 1999). In this case, the risk is of boredom and sleep rather than an inability to cope. Some workers have to deal with both of these extremes. For example, people in the control room of a nuclear power station may have little to do at night unless something goes wrong at which point rapid decisions with complex consequences may have to be made.

To summarize this discussion, the effects of light exposure at night can be divided into physiological and behavioural. That bright light can be used to suppress melatonin and shift the phase of circadian timing is undoubtedly correct. Such exposure to light can be used to correct the sudden misalignment between the circadian clock and the light–dark cycle caused by starting or finishing night-shift work. It can also be used to increase alertness at night without necessarily shifting the phase of the circadian clock simply by suppressing melatonin. What the consequences of light exposure at night are for task performance is much less clear, some tasks being more sensitive than others to being done when the body is telling the worker to sleep. Whether the suppression of melatonin and/or a shift in circadian phase produced by bright light exposure is sufficient to overcome the negative effects of trying to work at night depends on the structure of the task and the context in which it is being performed. This implies that there are no easy answers and no guarantees when it comes to predicting the effect of exposure to light at night on task performance (Figueiro and Rea, 2011; Kretschmer et al., 2011).

4.4.2 Light and Work by Day

It might be thought that for people who regularly work during the day and sleep at night, there would be no problem of circadian disruption. However, there are other non-image-forming systems to consider such as the awakening system involving the hormone cortisol (see Section 3.5). Exposure to high light levels in the morning increases cortisol concentration but exposure in the afternoon or evening does not (Scheer and Buijs, 1999; Ruger et al., 2006). As cortisol is believed to be involved in marshalling resources to undertake activities, it should not be surprising that exposure to bright light (1000 lx) for 5 h during the day has been shown to increase alertness and improve performance on a vigilance task, particularly when the rest of the day was spent under an illuminance much lower than usual (5 lx) and the people examined had had their sleep restricted on the two previous nights (Phipps-Nelson et al., 2003). Interestingly, Kaida et al. (2007) examined the effects of exposure to 2000 lx provided by daylight for 30 min in the early afternoon. They found a significant increase in alertness but no effect on the performance of a cognitive task. Whether this was caused by choosing an insensitive task or simply by the failure to affect cortisol, the increase in alertness being a psychological effect, remains an open question. Other studies have examined the effects of using light sources that provide greater stimulation to the ipRGC and hence to the non-image-forming systems, that is, light sources with a high correlated colour temperature. Viola et al. (2008) found that using fluorescent lamps with a correlated colour temperature (CCT) of 17,000 K increased alertness and subjective performance relative to lighting using a 2,900 K light source. Mills et al. (2007) found similar effects of using a high correlated colour temperature light source but other studies using a narrower range of correlated colour temperatures have failed to find any effects (Veitch and McColl 2001).

It is important to note that the conditions used in the studies described above have often been outside what would be considered normal for lighting practice, that is, very high illuminances or correlated colour temperatures. Smolders et al. (2012) have examined a set of somewhat more realistic conditions. The effect of two 1 h exposures at different times (morning and afternoon) to two illuminances (200 and 1000 lx) provided by light sources with a CCT of 4000 K on the performance of a vigilance task and on feelings of alertness and visibility was measured. The results showed that at the higher illuminance subjects felt less sleepy and more energetic at both times and had shorter reaction times at the vigilance task, particularly in the morning.

In response to the findings discussed earlier, a schedule of lighting involving changes in both the amount and spectrum of light delivered at different times of the day has been proposed. Specifically, a higher illuminance (700 lx maximum) at a higher correlated colour temperature (4600 K maximum) should be delivered in the morning and after lunch with a gradual transition to a lower illuminance (500 lx) from a lower correlated colour temperature light source (3000 K) at other times. So far, there is no evidence that such a schedule makes any difference to task performance in the real world, although this might have been due to the difference in the lighting conditions being diluted by the extensive daylight available in the office being studied (de Kort and Smolders, 2010).

All this suggest that whether or not lighting has a role over and above its effect on vision when the circadian timing system is correctly aligned to activity and, if it does, what lighting conditions are necessary, requires much more extensive and careful study before it will be possible to draw any definite conclusion.

4.4.3 Working with Sleep Deficit

So far, this consideration of working at night and by day has assumed that when not working there is an opportunity to sleep. However, there may be occasions in emergency or military situations when people have to work for much longer than usual and the desire to sleep has to be ignored. The question to be addressed here is what happens to performance in this situation and can lighting help.

Cajochen et al. (1999) studied the sleep and performance patterns of people kept awake for 32 h, that is, a period covering a conventional day, starting at 08:00 h and extending to 16:00 h the next day. Figure 4.18 shows the patterns in core body temperature and melatonin, both well-established circadian rhythms; eye blink rate, slow eye movements and stage 1 EEG patterns and ratings on the Karolinska sleepiness scale, all of which are related to sleep; and performance on a reaction time task, a mental arithmetic task and a short-term memory task. During the 32 h of wakefulness, the subjects were exposed to a constant illuminance of 15 lx. Figure 4.18 shows the expected pattern of decreased core body temperature and increased melatonin concentration at night. The sleep measures all show an increased propensity to sleep during the night with some recovery the next day. The performance measures all show a decrement in performance over the night with some recovery the following day, although not enough to recover to the level of performance achieved at the beginning of the trial. Of particular interest are the results on the reaction time task. What is evident in these data is the increase in range in reaction times at night. The 10% fastest reaction times at night are similar to what they are during the day but the

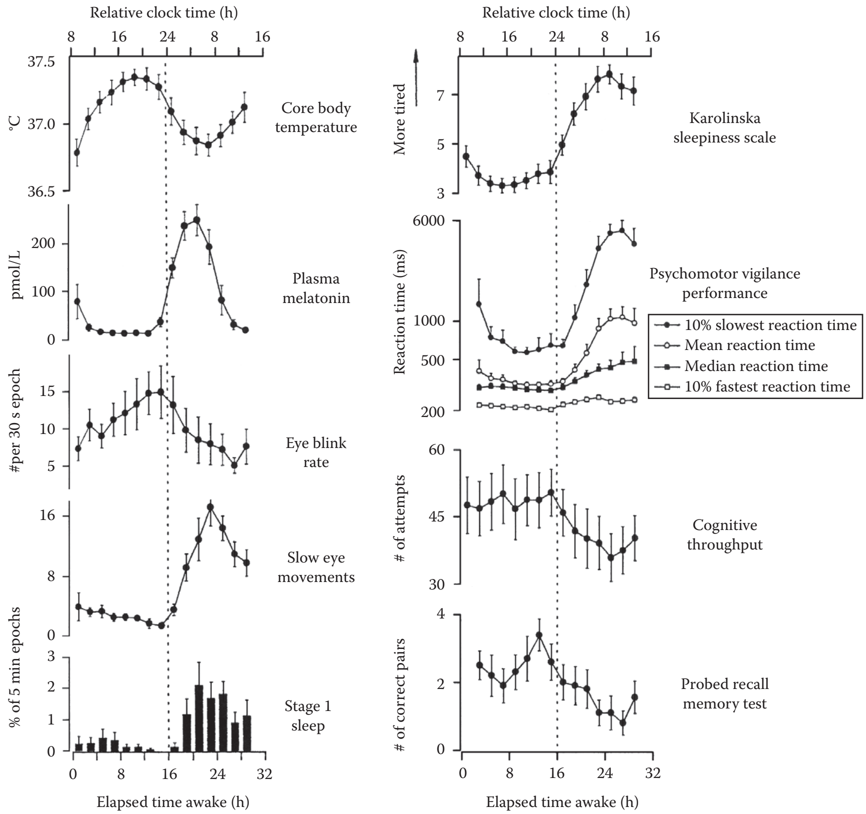

FIGURE 4.18 The time courses of core body temperature and melatonin concentration over 32 h. Time courses of measures of sleepiness, that is, mean eye blinks per 30 s, slow eye movements, stage 1 sleep and sleepiness ratings, over 32 h. Time courses of task performance for highly visible tasks requiring vigilance, mental arithmetic (cognitive throughput) and short-term memory, over 32 h. The dotted vertical line represents the subject's habitual bedtime. The error bars are standard errors of the means. (After Cajochen, C. et al., *Am. J. Physiol.*, 277, R640, 1999.)

10% slowest are 20 times slower. This spread in reaction times is consistent with one of the most commonly observed effects of continuous work without sleep, the presence of periods of no response or lapses (Wilkinson, 1969). These periods are correlated with periods of lower arousal and even microsleeps, measured by EEG signals (Cajochen et al., 1999). There are a number of task characteristics, which determine the likelihood of lapses occurring. Tasks that are of long duration (i.e. more than 30 min), monotonous and externally paced seem to be more likely to show lapses during sleep deprivation. Conversely, tasks which are considered of short duration, interesting or rewarding and which are self-paced are less likely to show lapses, although the self-paced task may be done more slowly to maintain the same level of accuracy (Froberg, 1985). It is important to realize that the change in the number of lapses is relative. All tasks show some decline with increasing sleep deprivation but the decline is less for the short duration, interesting, rewarding, self-paced tasks.

One aspect of task structure of particular interest is the extent to which short-term memory is required. Tasks requiring the use of short-term memory seem particularly sensitive to sleep deprivation, an observation consistent with the finding of Cajochen et al. (1999) that the frontal areas of the brain are more susceptible to sleep loss than occipital areas.

A similar circadian pattern of performance is evident in a study by Figueiro and Rea (2011). In this, some participants spent 27 h awake, starting at 07.00 h and finishing at 10.00 h the next day while others were allowed an opportunity to sleep for nearly 3 h (01.00–03.45 h) or nearly 7 h (01.00–07.45 h). When awake, all participants spent their time in a room illuminated by red light to less than 1 lx at the eye, except for a series of 50 min exposures to blue light provided by looking into a box illuminated by light-emitting diodes with a peak wavelength of 470 nm at the intensity required to produce an illuminance of 40 lx at the eye. These 50 min periods of exposure to blue light started at 08.10 h and occurred at 4 h intervals thereafter until the last exposure, which started at 08.10 h the next day. Immediately before and immediately after each 50 min exposure to blue light, participants performed three short-duration performance tasks, these being a simple reaction time, a forced choice reaction time and a matching-to-sample test. Figure 4.19 shows the performances achieved on these three tasks for the participants who were awake throughout the 27 h and those who had the opportunity to sleep for almost 7 h at night. Performance on all three tests was expressed as a throughput, this being a measure of accuracy and speed such that more accurate and faster performance led to a higher score. Examination of Figure 4.19 shows the expected pattern of performance increasing throughout the day, declining at night and recovering to some extent the next morning. However, the effect of exposure to blue light, which would be expected to be very effective in suppressing melatonin, is less clear. At the end of the night, that is, after 25 h had elapsed, exposure to blue light is associated with an increase in performance for both those who have been awake all night and those who have had the opportunity to sleep, for all three task types, an effect that may simply be the cortisol awakening response in action (see Section 3.5). During the night after 21 h had elapsed, exposing the group who are awake to blue light seems to produce an improvement in performance for the simple reaction time task but not for the forced choice reaction time or the matching-to-sample task, both of which require the use of short-term memory. From midday to midnight and therefore ignoring the first exposure which may be contaminated by practice effects, there is sometimes an increase and sometimes a decrease in performance on the three task types after exposure to blue light, although all three tasks show an improvement following exposure to blue light at midnight, that is, after 17 elapsed hours, although this was preceded by a decline in performance from that achieved at 20.00 h, that is, after 13 elapsed hours.

As for the effect of being able to sleep, it is interesting to note that on the morning of the second day, the performance of the participants who had the opportunity to sleep is noticeably better for the more complex forced choice reaction time and matching-to-sample tasks than is the case for those who had been awake all night. This is not the case for the simple reaction time task. Interestingly, there are differences between those who had the opportunity to sleep and those who had not on all three task types for the midnight exposure (after 17 elapsed hours), although at that

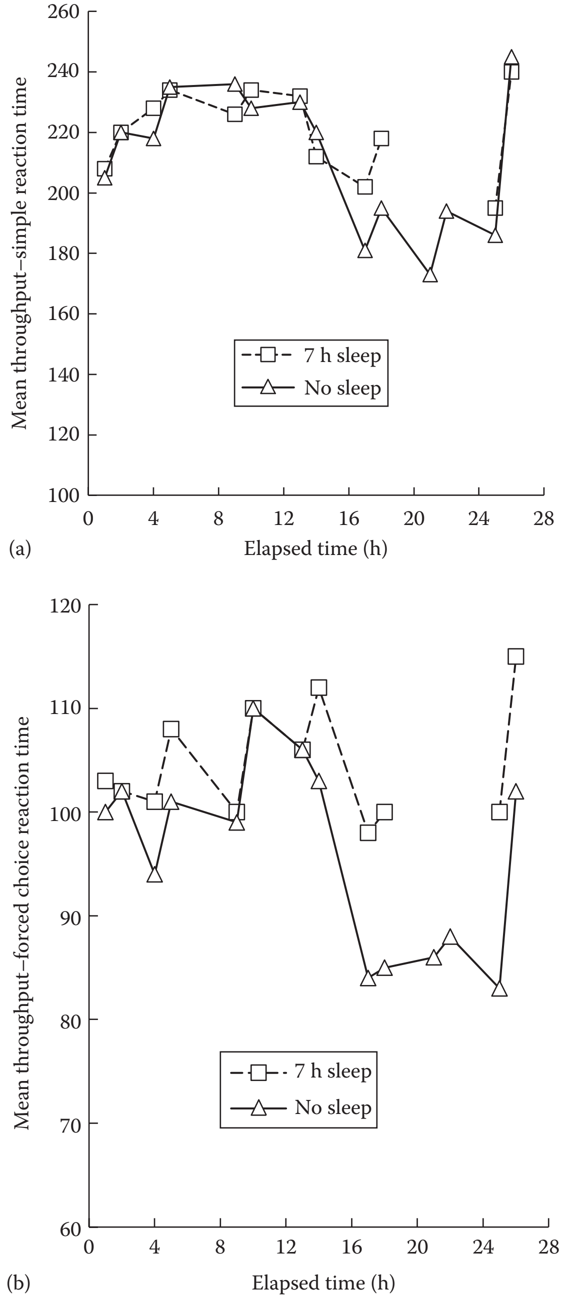

FIGURE 4.19 Effect of exposure to 40 lx of blue light for 50 min at different times over 27 h on performance of (a) simple reaction time and (b) forced choice reaction time for people who could sleep for 7 h starting at 01.00 h or who were not allowed to sleep. The timing started at 07.00 h.

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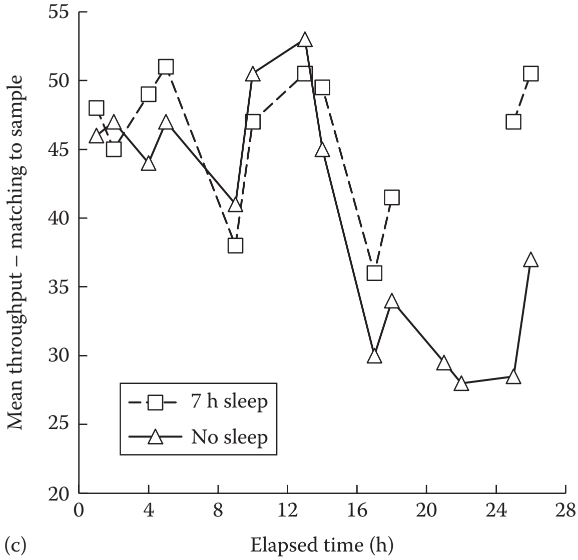


FIGURE 4.19 (continued) Effect of exposure to 40 lx of blue light for 50 min at different times over 27 h on performance of (c) matching-to-sample tests, for people who could sleep for 7 h starting at 01.00 h or who were not allowed to sleep. The timing started at 07.00 h. (After Figueiro, M.G. and Rea, M.S., *Lighting Res. Technol.*, 43, 3439, 2011.)

stage both groups had been awake for the same length of time. This might be an effect of motivation rather than physiology but it does serve to demonstrate the interaction of the different routes between lighting and task performance as well as the difficulty likely to be experienced in attempting to unravel the multiple possible causes of changes in cognitive performance. Overall, the answers to the questions posed earlier are that working with a sleep deficit leads to a reduction in performance during the night that is only partly eliminated with the arrival of day. Exposure to blue light during the night improves the performance of some tasks but not all.

There is also some support for the idea that light exposure during the day can influence how we perform at night. Figueiro et al. (2013b) measured the performance of a 54 min long tracking task at 4 h intervals for a period of 26 h starting at 07:00. The interesting result was that exposure to more than 500 lx provided by daylight from 07:00 to 17:00 and 65 min of short-wavelength light every 4 h starting at 08:00 produces better performance late in the night than spending the entire 26 h in darkness.

It is important to note that in all the studies described earlier, the sleep deficit was accumulated over one night. However, it is also possible to accumulate a sleep deficit slowly over many nights. Canazei et al. (2013) examined the effect of dynamic lighting on the performance of female workers doing permanent morning shifts on an electronics assembly line. The morning shift started at 06.00 h and finished around 14.00 h. Workers doing such shifts are frequently found to have a sleep deficit. The dynamic lighting was provided by high correlated colour temperature (6500 K) light sources, the illuminance on the task starting at 1000 lx but increasing to 2000 lx over a 2 h period, starting at 08.00 h, the higher illuminance being maintained until the end of the shift. The dynamic lighting was found to improve mean handling time for the electronics assembly work in winter but not in summer. This improvement was relative to the mean handling time achieved by the same workers under a fixed illuminance of 1000 lx provided by 4000 K light sources. It is possible that the difference in the effect of dynamic lighting between winter and summer is due to the limited availability of daylight before and after the shift in winter. Clearly, lighting has a role to play in alleviating the effects of sleep deficit on work performance, but a lot more careful research is needed before it can be used with confidence.

4.5 LIGHT, WORK, MOOD AND MOTIVATION

Lighting does not produce work, it simply makes work requiring the use of the visual system possible. How much work is done and of what quality depend on many other variables but one of the most important is motivation. The motivation to work is influenced by many fundamental aspects of life, such as reward, risk, need, fear, fun, pride, coercion and ambition, but there is no doubt that the working environment also matters. So what role does lighting have to play in improving task performance by increasing motivation? At its simplest, if the lighting causes visual discomfort by failing to make what needs to be seen clearly visible or introduces distraction through glare or flicker or just fails to meet expectations, it is likely to generate negative feelings. Fortunately, the lighting conditions that cause visual discomfort are well known and easy to avoid (see Chapter 5) and expectations are largely set by what is current lighting practice. This means that for most forms of work, adherence to current lighting standards and practice is enough to ensure that negative feelings about lighting do not occur. But is it possible to eliminate the negative and accentuate the positive? There can be no doubt that lighting can be used to modify an observer's mood (Baron et al., 1992; McCloughan et al., 1999), at least over the short term, although whether such emotions are sustained over continuous exposure is unknown. Inducing positive feelings can be achieved by two approaches. One seeks to provide the required level of task visibility, without discomfort, and to integrate the lighting with the architecture so that the space becomes a thing of beauty and a source of pleasure (CIE, 1998a). The other recognizes that people differ widely in the preferences for the amount of light provided on a task and gives the individual some control over the lighting of their workplace (Boyce et al., 2006a). It should be noted that these two approaches are not mutually exclusive, although the former tends to be preferred in places that people visit for enjoyment, such as restaurants, while the latter is more common in everyday places of work such as offices.

Being able to generate a positive response to lighting is important because pleasant feelings produced by commonplace events or circumstances, a phenomenon known as positive affect, have been shown to influence cognition and social behaviour. Specifically, positive affect has been shown to increase efficiency in making some types of decisions and to promote innovation and creative problem solving. It also changes the choices people make and the judgements they deliver. For example, it has been shown to alter people's preferences for resolving conflict by collaboration rather than avoidance and also to change their opinions of the tasks they perform

(Isen and Baron, 1991). The factors that determine positive affect are both small and wide: small, because the stimuli that have been shown to generate positive affect are low-level stimuli, ranging from receiving a small but unexpected gift from a manufacturer's representative to being given positive feedback about task performance, and wide because positive affect can be influenced by the physical environment, the organizational structure and the organizational culture. Lighting is clearly part of the physical environment, and lighting conditions such as the illuminance and the correlated colour temperature of the lighting have been shown to change mood (McCloughan et al., 1999) and behaviour in a way consistent with positive affect (Baron et al., 1992). But it has to be admitted that lighting is just one among many factors that influence mood and hence motivation, and once visual discomfort is eliminated, it may be a second- or third-order factor.

This raises the question of what evidence there is that lighting, as currently practiced, can influence task performance during the day when task visibility is held constant. The answer is not much. One early attempt to demonstrate the effects of lighting quality on the performance of office tasks produced a confusing array of small effects (Veitch and Newsham, 1998a) that may or may not have been associated with differences in visibility. In another study where task visibility was deliberately controlled, different light distributions had no effect on sustained task performance, despite the light distributions being considered very different in quality by lighting experts (Eklund et al., 2000). Similarly, Fostervold and Nersveen (2008) found very few statistically significant effects of different proportions of direct and indirect lighting on office workers' health, well-being and cognitive performance. Probably the most interesting of the attempts to demonstrate the benefits of better lighting quality on task performance is that of Boyce et al. (2006b). This involved two experiments undertaken in a simulated office with temporary office workers working for 1 day under each of a number of different lighting installations. Experiment 1 had 4 lighting conditions: a regular array of recessed parabolic luminaires, direct/indirect luminaires with no control, direct/indirect luminaires with a switchable desk lamp and workstation-specific direct/indirect luminaires with control over the direct light output. Experiment 2 contrasted 2 conditions with no individual lighting control: a regular array of recessed prismatic-lensed luminaires and suspended direct/indirect luminaires. There was very little daylight in the office. Subjects followed the same procedure each day, the procedure consisting of a mixture of activities designed to measure their perceptions and feelings, visual capabilities, motivation, vigilance, typing speed, cognitive task performance and work strategies and their social behaviour. Subjects were able to discriminate between the lighting installations. More subjects considered the direct/indirect systems to be comfortable than the direct-only systems, with a further increase in comfort associated with individual control (see Table 5.2). However, there were no simple main effects of lighting quality on the performance of any task, although the expected changes in performance associated with task visibility, practice and fatigue were found.

For those who believe in the benefits of good-quality lighting, such results must be disappointing but they should not abandon hope entirely. These experiments were built around a series of hypotheses formed into what is known as a linked mechanisms map (Wyon, 1996). This is a logical structure that attempts to set out the

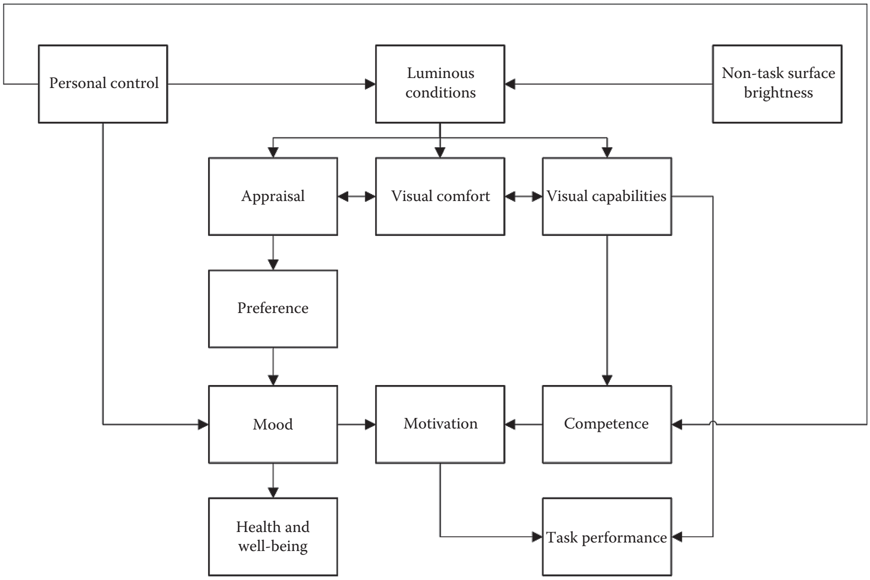


FIGURE 4.20 A hypothetical linked mechanisms map. (After Veitch, J.A. et al., *Lighting Res. Technol.*, 40, 133, 2008.)

paths by which the independent variables, in this case, the lighting installations, the reflectances of the surfaces forming the work cubicles and the degree of individual control over the lighting, influence the dependent variables, in this case, feelings of health and well-being and task performance. Figure 4.20 shows the hypothesized linked mechanisms map used. This is based on the observations that giving people individual control of lighting will change the lighting conditions as will varying the reflectance of the surfaces in the working space. Changes in luminous conditions can affect visual comfort and visual capabilities, the latter having a direct effect on the performance of visual tasks and possibly an influence on the person's feelings of competence to do the task. Changing the luminance conditions may also affect the person's appraisal of the lighting and, when that is compared to the person's preferred conditions, may change mood. Changes in mood may affect feelings of health and well-being and motivation to do the task and the latter, in turn, may affect task performance. Finally, giving a person control over their lighting is expected to influence their mood directly with consequences for feelings of health and well-being and for motivation. The procedure followed throughout the day ensured that each step on the paths through the linked mechanisms map could be statistically tested. The initial analysis of the results using analysis of variance and nonparametric tests (Boyce et al., 2006b) and a more sophisticated statistical analysis done later, using mediated regression analysis (Veitch et al., 2008), led to a linked mechanisms map constructed from proven steps (Figure 4.21). The initial analysis showed that different lighting installations were perceived differently, that conditions that improved the visibility of tasks led to better task performance and that individual control over the lighting

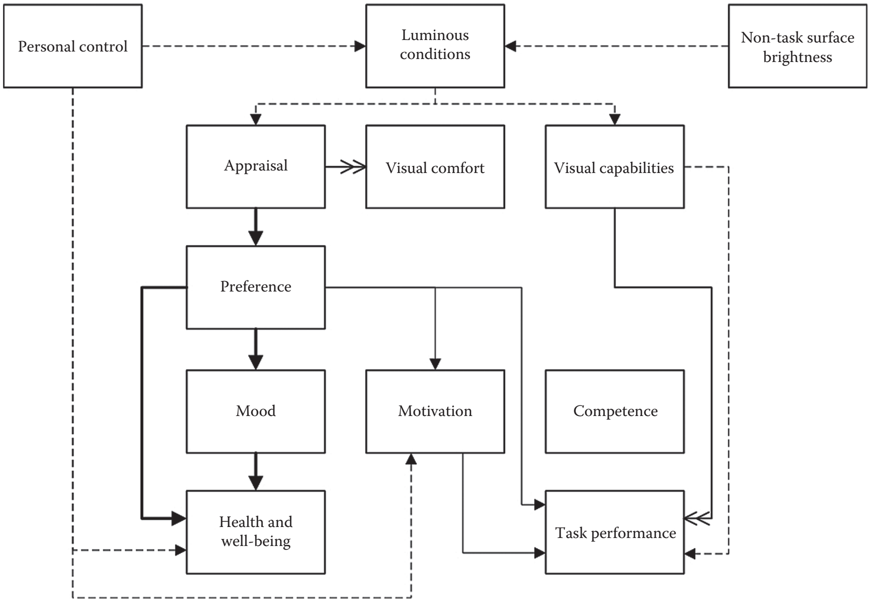


FIGURE 4.21 A linked mechanisms map showing the lighting condition test results by dashed lines and the mediated regression test results by solid lines. The thick solid lines show the appraisal path and the thin black lines with double arrows show the vision path. (After Veitch, J.A. et al., *Lighting Res. Technol.*, 40, 133, 2008.)

improved motivation and well-being. The latter analysis confirmed these findings in that the path with the largest effect size was from appraisal to health and well-being. Participants who perceived the office lighting to be of higher quality rated the space as more attractive and felt they were in a better mood and had a feeling of greater well-being. Another path was through visual capabilities to task performance. The initial analysis failed to reveal any links between these two paths, that is, between the appraisal path and the vision path, but the later analysis did although the effect sizes were small. These links run from the preferred lighting conditions directly to task performance or indirectly through motivation. The evidence for these links is weak, and in one sense, the links are counterintuitive because they are negative, which means less attractive lighting is likely to produce better task performance.

All that can be confidently concluded from this work is that, for the lighting conditions studied, which were representative of current good practice in office lighting, and for the tasks studied, which were visually easy and representative of simple office tasks, changing the lighting of the space can influence feelings of health and well-being but will only affect task performance if the visibility of the task is also changed. There are two plausible reasons for the failure to find the expected links between mood, motivation and performance. The first is simply the range of lighting conditions and tasks studied. It may be that more extreme lighting conditions and tasks would have shown a link. The second is that the experience of each lighting condition was limited to one day. It may be that lighting conditions that can be ignored for one day become more important when one is exposed to them for many months.

Given that the lighting installations and tasks used were representative of offices today, making the office lighting worse or the tasks more difficult would be academically interesting but practically irrelevant. About the only area that would be worth studying for offices would be to examine the response to the provision of daylight. Kuller et al. (2006) carried out an extensive survey of the effect of lighting and colour on mood in workplaces in Argentina, Saudi Arabia, Sweden and the United Kingdom. Interestingly, it was found that the actual illuminance provided by the lighting had no statistically significant effect on mood because despite considerable variation, most respondents considered the lighting provided to be just right. However, the distance from a window did have a statistically significant effect on mood, at least in February when daylight is limited at some latitudes. People close to a window (<5 m) or far from a window (10–100 m) experienced a more positive mood than those near the window but not quite near enough (5–10 m). This is consistent with the fact that people prefer to work by daylight when at all possible (see Section 7.3.1).

It might also be fruitful to consider widening the applications being examined and the definition of what constitutes a task. The retail and hospitality industries use a much wider range of lighting conditions than offices, and for them, customer behaviour is the most relevant form of performance. Support for this idea comes from a study that established a correlation between the presence of skylights and the value of sales in a supermarket, the presence of skylights leading to higher sales (Heschong et al., 2002a). It is unclear whether this effect is due to the presence of daylight, per se, or because the illuminances are much higher in the daylit part of the supermarket than in the electrically lit part, so the visibility of the merchandise is better or whether the message delivered by the higher ceiling and the variation in daylight is important. Nonetheless, studies in these areas are more likely to produce interesting results than yet further simulation studies in offices.

As for the second plausible reason for the failure to establish a link between mood, motivation and performance, the limited exposure time, this suggests an alternative approach to examining the effects of good-quality lighting on performance: a move into the field. Field studies in this area would have a number of advantages. First, such investigations would have a higher level of realism than is possible in a simulation experiment, which cannot fully recreate the context of a functioning workplace. Effects involving visibility occur regardless of context, but mood and motivation effects are context dependent. Studying these latter effects requires real people in real organizations. Second, field investigations would allow the accumulation of results over an extended period of time. Third, field research into lighting effects on people at work would allow for the possibility of measuring the effects of lighting conditions on aspects of performance and behaviour at an organizational rather than an individual level. For example, absenteeism, recruitment and staff retention are important considerations to organizations.

Of course, a move to long-term field studies requires the recognition of two facts. The first is that lighting is just one of the many factors affecting mood and motivation, and in many situations, it may be of minor or even negligible significance if current lighting practice is followed. The second is that the relationship between mood, motivation and task performance is inevitably a matter of probability rather than certainty. If this is accepted, then one important task would be to change the qualitative relationships shown in Figure 4.21 into quantitative relationships using structural equation modelling, a statistical technique designed to produce a model of the causal relationships between three or more variables, considered as a system (Beckstead and Boyce, 1992). Veitch et al. (2007) report such a field study. Using this technique and working with the answers to a questionnaire by 714 office workers from 9 offices in North America, they constructed a structural equation model showing the relationships between satisfaction with lighting, satisfaction with acoustics/privacy, satisfaction with ventilation/temperature, overall satisfaction with the environment and job satisfaction. Job satisfaction is an important outcome because of its robust connections to organizational commitment, intention to leave and actual turnover of staff (Carlopio, 1996; Wells, 2000). Moreover, organizations with higher employee job satisfaction have been found to have more satisfied customers and better business unit financial performance (Harter et al., 2002). As might be expected, the model showed that satisfaction with lighting was not the most important contributor to overall satisfaction with the environment and overall satisfaction with the environment was a minor contributor to job satisfaction explaining only 9% of the variance in job satisfaction. Nonetheless, studies of this type, as well as more conventional long-term studies involving actual measurements of various aspects of organizational efficiency, could provide a much clearer picture of the role of lighting quality in determining the productivity of people at work.

4.6 SUMMARY

Lighting conditions can affect task performance through three routes: the visual system, the circadian timing system and changes in mood and motivation. The impact of lighting conditions on the visual system and hence on visual performance is determined by the size, luminance contrast and colour difference of the task and the amount, spectrum and distribution of the lighting. The impact of lighting on the circadian timing system is determined by the amount, spectrum, timing and duration of the exposure to light. The impact of lighting through mood and motivation is determined by the message it sends.

The majority of studies of the effect of lighting conditions on work have concentrated on the impact through the visual system. Early studies were field studies. While these studies have a high face validity and frequently demonstrated the expected increase in task performance with increasing illuminance, the conclusions that can be drawn from them are limited to the specific tasks studied. Simulated work in the laboratory has also been done, with better experimental control than the field studies, but with little increase in understanding.

An analytical approach using a standard task measured over a wide range of conditions has served to demonstrate, qualitatively, the effects of increasing illuminance on visual performance. They are that increasing illuminance follows a law of diminishing returns, that is, that equal increments in illuminance lead to smaller and smaller changes in visual performance until saturation occurs; that the point where saturation occurs is different for different sizes and contrasts of critical detail; that larger improvements in visual performance can be achieved by changing the task than by increasing the illuminance, at least over any illuminance range of practical interest; and that it is not possible to make a visually difficult task reach the same level of performance as a visually easy task simply by increasing the illuminance over any reasonable range. The overall concept is that the shape of visual performance can be considered as a plateau and an escarpment, the point being that over a wide range of task and lighting variables, the change in visual performance is slight but at some point one or more of the relevant variables will decline too far and then performance will start to deteriorate rapidly.

While this understanding is useful, it is not enough to make quantitative predictions of the effect of lighting conditions on visual performance for all tasks, although it is possible for some. However, the RVP model of visual performance has been shown to make accurate predictions for tasks that are dominated by the visual component; that do not require the use of peripheral vision to any extent; that present stimuli to the visual system that can be completely characterized by their visual size, luminance contrast and background luminance only; and that have values for these variables that fall within the ranges used to develop the model. Two other variables that are known to affect visual performance but are not included in the RVP model are retinal image quality and a colour difference between the task and its immediate background. Poor retinal image quality will degrade visual performance but a noticeable colour difference can sustain a high level of visual performance when luminance contrast is low.

The effects of lighting on task visibility and hence visual performance will be evident at all times, but as soon as the circadian timing system is considered, when the work is done becomes important and the consequences apply to all types of tasks, not just to visual tasks. When trying to work at night, people will experience difficulty in performing many sorts of task because their circadian timing system is telling them to sleep. There are two approaches to reducing these difficulties. The first is to use controlled exposure to light to shift the phase of the circadian rhythm so that the time of wakefulness corresponds to the time when work is to be performed. This is possible in principle but little used in practice because to be effective light exposure has to be controlled over the whole 24 h. The other approach is to use exposure to light to suppress the hormone melatonin and hence increase alertness at night, which, in turn, should lead to an improvement in the performance of some tasks. Studies of night-shift work have shown that the tasks most sensitive to work at night, and hence which benefit most from light exposure, are of two types. One is cognitively complex requiring the mental manipulation of information. The other is a vigilance task, where attention has to be paid to unchanging information in case something happens but it rarely does. In this case, the risk is of boredom and sleep rather than an inability to cope.

It might be thought that for people who regularly work during the day and sleep at night, there would be no problem of disrupting the circadian timing system. However, there are other elements of the non-image-forming system to consider such as the awakening system involving the hormone cortisol. Attempts to demonstrate that exposure to high light levels and high correlated colour temperatures during daytime affect task performance other than through visibility have produced mixed outcomes. This suggests that whether or not lighting has a role over and above its effect on vision when the circadian timing system is correctly aligned to activity and, if it does, what lighting conditions are necessary requires much more extensive and careful study before it will be possible to draw any definite conclusion.

In emergency or military situations, it may be necessary for people to work for much longer than usual without sleep, but what happens to performance in this situation and can lighting help? Over 32 h of wakefulness with a constant illuminance, people showed the expected circadian pattern of a decreased core body temperature and increased melatonin concentration at night with some recovery the next day. Similarly, task performance shows a decrement in performance over the night with some recovery the following day, although not enough to recover to the original level. Exposure to light during the night improves the performance of people with a sleep deficit but only for some tasks and at some times.

The other route by which lighting can affect task performance is through mood and motivation. Lighting does not produce work, it simply makes work requiring the use of the visual system possible. How much work is done and of what quality depend on many other variables but one of the most important is motivation. So what role does lighting have to play in improving task performance by increasing motivation? At its simplest, if the lighting causes visual discomfort by failing to make what needs to be seen clearly visible or introduces discomfort through glare or flicker or just fails to meet expectations, it is likely to generate negative feelings. Fortunately, the lighting conditions that cause visual discomfort are well known and easy to avoid, so adherence to current lighting standards and practice is usually enough to ensure that negative feelings about lighting do not occur. But can lighting produce positive feelings? There is no doubt it can, at least over the short term, although whether such emotions are sustained over prolonged exposure is unknown. Positive feelings can be induced in two ways. One is to provide the required level of task visibility, without discomfort, and to integrate the lighting with the architecture so that the space becomes a thing of beauty and a source of pleasure, that is, better lighting quality. The other recognizes that people differ widely in the preferences for the amount of light provided on a task and gives the individual some control over the lighting of their workplace. Being able to generate a positive response to lighting is important because pleasant feelings produced by commonplace events or circumstances, a phenomenon known as positive affect, have been shown to influence cognition and social behaviour. Unfortunately, a number of attempts to show that providing more interesting lighting of the space without changing the task visibility have failed to find any effect on task performance. Yet, another set of studies based around testing a set of hypothesized links between lighting conditions, task performance and feelings of health and well-being have shown that improving lighting quality and giving people individual control of lighting can certainly enhance feelings of health and well-being, but such feelings have little effect on task performance. There are two plausible reasons for this failure. The first is simply that the range of lighting conditions and tasks studied, which were representative of office lighting and office work, may have been too restricted. The second is that the experience of each lighting condition was limited to one day. The first reason suggests that it might be fruitful to consider widening the applications being examined beyond the office as well as the definition of what constitutes a task. The retail and hospitality industries use a much wider range of lighting conditions than offices, and for them, customer behaviour is the most relevant form of performance. Studies in these areas are more likely to produce interesting results. The second reason suggests a move to long-term field studies. Such investigations would have a higher level of realism than is possible in a conventional laboratory or simulation study, neither of which can fully recreate the context of a functioning workplace. Effects of performance involving visibility occur regardless of context, but mood and motivation effects are context dependent. Studying these latter effects requires real people in real organizations. Field studies would also allow the accumulation of results over an extended period of time and would make it possible to measure the effects of lighting conditions on aspects of performance and behaviour at an organizational rather than an individual level. This last point is attractive because there is already evidence that greater satisfaction with lighting conditions contributes to greater environmental satisfaction which, in turn, leads to greater job satisfaction. Job satisfaction is an important outcome because of its robust connections to organizational commitment, intention to leave and actual turnover of staff.

Overall, this review of how lighting conditions affect the ability to work has ranged from the certain to the possible. The certainty relates to the effect of visibility on visual performance and the role of lighting on phase shifting of the circadian timing and the increase of alertness at night. Uncertainty increases as we move from visual performance to task performance and from increasing alertness at night to the consequences for different types of task. Uncertainty reaches its peak when attempts are made to understand the effects of lighting the space on task performance driven by changes in mood and motivation. Despite the development of a validated model of RVP, there is still much to learn about the relationship between lighting and work. It is unlikely that much progress will be made until it is recognized that for many of the effects being sought, lighting is just one variable among many and hence that the link between lighting and work is a matter of probability rather than certainty.

5 Lighting and Visual Discomfort

5.1 INTRODUCTION

In addition to ensuring people can see what needs to be seen, most lighting installations are designed to ensure visual comfort. But what is visual comfort? One view is that visual comfort is simply the absence of visual discomfort. This is logical but not particularly helpful. While it is undoubtedly true that some lighting conditions can cause discomfort, is it also true that there is a positive sense of comfort to be manipulated after all sources of discomfort have been eliminated? Zhang et al. (1996) and Helander and Zhang (1997) examined the question of perceptions of comfort and discomfort for seating. They found that perceptions of comfort and discomfort were independent of each other, rather than a continuum. Specifically, the perception of discomfort experienced when sitting was characterized by feelings of pain, soreness and numbness that changed over time and could be related to the physiological stresses the seating produced. Perceptions of comfort were related to feelings of well-being and aesthetics that changed little over time and could be linked to perceptions of luxury and plushness. Applying this framework to lighting suggests that most of the recommendations made by authoritative bodies about desirable lighting conditions are concerned with eliminating visual discomfort, while how lighting designers make a living is to provide visual comfort. This chapter is devoted to the topic of light and visual discomfort.

5.2 CHARACTERISTICS OF VISUAL DISCOMFORT

Visual discomfort has a number of distinctive features. First, visual discomfort is characterized by large individual differences, so much so that some of the early studies of discomfort glare used panels of subjects chosen for the reliability of their responses rather than their representative nature (Hopkinson, 1963). Part of this individual variability is due to the fact that asking people to identify when a condition becomes uncomfortable involves both a discrimination and a criterion, that is, the individual has to be able to tell when a condition occurs and then decide if this is uncomfortable or not. For lighting, the discrimination part of this process is likely to be determined by the characteristics of the visual system, which inevitably includes some individual variability, but the criterion part adds another element of variability. The problem of including the criterion is that what lighting is considered uncomfortable, or more importantly, acceptable, is based on past experience and hence on expectations and on attitudes. People have expectations about all sorts of things in life, from relatively simple pieces of hardware such as cars and computers to more sophisticated concerns such as health care and personal relationships, and these expectations are likely to change over time. There is no reason why lighting should be exempt from such shifting expectations. The problem comes about because different people, in the same or different cultures, have different experiences and hence different expectations. The effect of expectations was evident in an attempt to get lighting designers worldwide to rate the quality of lighting in a series of offices furnished with the cubicle systems common in North America. Agreement could only be produced by separating the reactions of designers working in North America, who had experienced similar installations, from those presented by the non-North American designers, who had no such experience (Veitch and Newsham, 1996).

Second, visual discomfort is dependent on context. Lighting conditions that are considered uncomfortable in one application may not be considered uncomfortable in another. For example, flicker in an office is undesirable, but in a nightclub, it is used to generate excitement.

Third, the determinants of visual discomfort cover the whole visual field. This separates visual discomfort from visual performance. The aspects of lighting relevant to visual performance are generally restricted to the immediate task area. The aspects of lighting affecting visual discomfort can occur anywhere within the lit space.

5.3 GENERAL CAUSES OF VISUAL DISCOMFORT

Visual discomfort can be identified by many different measures, ranging from the frequent occurrence of health symptoms that can be linked to exposure to the lighting to such vagaries as whining about the lighting. Among the symptoms that may be taken as markers of visual discomfort are red, sore, itchy and watering eyes; headaches; and aches and pains associated with poor posture. Of course, there are many other possible causes of these symptoms. Thus, the occurrence of such symptoms should not be taken to mean that the lighting is at fault until the alternatives have been considered. A similar situation prevails for vague whining about the lighting. Photometric measures relevant to the specific aspect of the lighting complained of should be made before accepting the complaints. If the photometric measures are consistent with the complaints, then the complaints are probably justified. Systematic procedures for evaluating the lighting of offices and car parks and using both peoples' opinions and photometric quantities have been developed (Eklund and Boyce, 1996; Boyce and Eklund, 1998).

In its most general sense, lighting is designed to enable the visual system to extract information from the visual environment. Therefore, this examination of the causes of visual discomfort will start by considering the aspects of the visual environment that are likely to influence the ability to extract information. They are as follows:

Visual task difficulty: Any visual task that has visual stimuli close to threshold contains information that is difficult to extract. This in itself leads to headaches and fatigue, but if the problem is of small visual size, there is the possibility of an additional effect. The usual reaction to a small visual size is to bring the task closer. As the task is brought closer, the accommodation mechanism of the eye (see Section 2.3.3) has to exert pressure on the lens to increase its optical power and to keep the retinal image sharp. This adjustment can lead to muscle fatigue and hence symptoms of visual discomfort.

Under- and overstimulation: Discomfort occurs either when there is no or little information to be extracted or when there is an excessive amount of repetitive information. Examples of no-information anywhere in the visual field occur rarely in real life, which is just as well because prolonged exposure to a very uniform field of luminance created by wearing translucent goggles produces severe disturbances of visual perception that can cause anxiety and panic (Corso, 1967). Less extreme conditions, such as might occur in an all-white room lit indirectly, can still be uncomfortable, as anyone who has looked into an integrating sphere for any length of time will know. As for overstimulation, the important point is not only the total amount of visual information but also the presence of large areas of the same spatial frequency. Wilkins (1995) has associated the presence of large areas of specific spatial frequencies in printed text with the occurrence of headaches, migraines and reading difficulties.

Distraction: The human visual system has a large peripheral field that detects the presence of objects that are then examined using the small, high-resolution fovea (see Section 2.2.4). For this system to work, objects in the peripheral field that are much brighter than the background, moving or flickering have to be easily detected. If, upon examination, these bright, moving or flickering objects prove to be of little interest, they become sources of distraction because their attention gathering power is not diminished after one examination. Ignoring objects that automatically attract attention is stressful and can lead to symptoms of visual discomfort.

Perceptual confusion: The visual environment consists of a pattern of luminances, developed from the differences in reflectance of the surfaces in the field of view and the distribution of illuminance on those surfaces. Perceptual confusion can occur when there is a pattern of luminances present that is solely related to the illuminance distribution and conflicts with the pattern of luminances associated with the reflectances of the surfaces.

5.4 SPECIFIC CAUSES OF VISUAL DISCOMFORT

There are many different aspects of lighting that can cause visual discomfort. Insufficient light for the performance of a task has already been considered (see Chapter 4) and will not be discussed further. Rather, attention will be devoted to uniformity, glare, veiling reflections, shadows and flicker.

5.4.1 Uniformity

While exposure to a completely uniform visual field is undesirable, it is also possible to have too much non-uniformity. For this reason, recommendations for lighting practice usually include something about illuminance uniformity (BSI, 2011a).

Saunders (1969) measured the acceptability of different illuminance ratios in a windowless room by having subjects occupy two desks successively and then asking them how reasonable it was to have such a difference in illuminance. Figure 5.1 shows the outcome. It can be seen that as the uniformity ratio, measured as the minimum/maximum illuminance, dropped below about 0.7, there was a marked increase in the percentage of people considering the lighting pattern unreasonable. This finding has

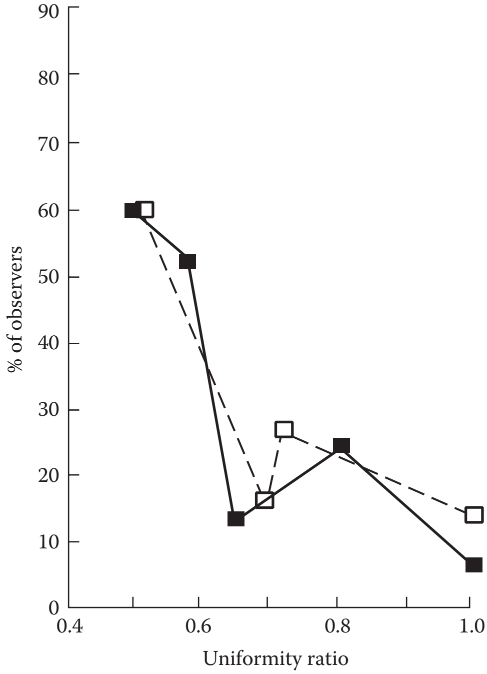


FIGURE 5.1 The percentage of observers considering the uniformity of illuminance between two desks unreasonable, plotted against uniformity ratio. Uniformity ratio is the lower illuminance/higher illuminance. For the continuous line, the variation in uniformity was achieved by dimming one luminaire. For the broken line, different spacing of luminaires was used to produce the change in uniformity ratio. (After Saunders, J.E., *Lighting Res. Technol.*, 1, 37, 1969.)

since been confirmed (Slater et al., 1993), also in a windowless room. However, a moment's consideration will suggest that this criterion probably only applies where the lighting installation is perceived by the occupants to be intended to produce a uniform distribution of illuminance. In rooms with large windows, the illuminance on a desk close to the window will be much greater than on a desk far from the window, so the illuminance uniformity ratio will be much less than 0.7, but few complaints are heard. Similarly, studies in offices where the luminaires can be individually switched or dimmed have shown that wide variations in the illuminance on desks can be tolerated, without complaint (Boyce, 1980; Moore et al., 2002a,b, 2003). What this implies is that where non-uniformity of illuminance is expected or is exchanged for some other benefit, such as a view out of a window or individual control of the lighting, illuminance uniformity requirements can be relaxed. This in turn suggests that illuminance uniformity limitations applied across the whole space are more of a design requirement adopted to ensure that no one has insufficient illuminance for their work rather than an intrinsic requirement of the visual system.

So far, this discussion of illuminance uniformity has been large scale, that is, variations between desks and across large spaces. However, there is another level at which uniformity needs to be considered – that of the individual work surface.

Two potential sources of discomfort for workplace lighting are distraction and perceptual confusion. Non-uniformity of illuminance is unlikely to cause perceptual confusion unless the illuminance pattern has a sharp edge so that it could be mistaken for a change in reflectance. As for distraction, this can occur where there are areas of high illuminance adjacent to the work area. Studies of peoples' reactions to several different forms of local lighting for desks have shown that the most preferred form is the one that provides a uniform illuminance over an area of about 1 m^2 where the work is to be done and lower illuminances outside that area (Boyce, 1979a). The latest European Standard (BSI, 2011a) sets out a pattern of relative illuminances for work surfaces so as to avoid distraction. The recommended minimum illuminance uniformity of the task area, measured as the minimum illuminance/average illuminance, can vary from 0.4 to 0.7 depending on the application. Where a uniform lighting system is installed, this is the only uniformity recommendation of interest. However, where a task/ambient lighting system is installed, there are other criteria to be considered. For this situation, the task area is assumed to have a surround area spreading at least 0.5 m from the edge of the task area which itself is enclosed by a background area spreading up to 10 m from the edge of the surround area. The average illuminance recommended for the surround area varies from 0.5 to 0.7 of the average illuminance of the task area, depending on the application, and the average illuminance of the background should be at least one-third of the average illuminance of the surround. Following such recommendations will ensure that distraction due to non-uniformity is unlikely to occur.

From the aforementioned discussion, it should be clear that most lighting recommendations related to uniformity have to do with the distribution of illuminance. However, what the visual system sees is the pattern of luminance. Fortunately, for simplicity, common practice makes this less of a problem for workplace lighting than might be supposed because the common practice is to make the working surface of uniform reflectance, the variations in reflectance being introduced by the materials placed on the work surface. Figure 5.2 shows the percentage of people finding different levels of illuminance uniformity across a task acceptable for four different tasks using different materials on a desk and for the desk itself without a task (Slater and Boyce, 1990). The different conditions lead to slightly different results but the trends are consistent: decreasing illuminance uniformity increases the percentage who find the conditions unacceptable. Also, it is clear that a minimum illuminance uniformity ratio of about 0.7 will be acceptable for most people.

Given that a uniform illuminance is provided over the work surface, there is still the possibility that discomfort could occur because of a poor choice of desk surface reflectance relative to the reflectance of the task materials. Touw (1951) examined this question by having people copy figures onto white paper while sitting at six different grey desks, each with a different reflectance. The results showed that the preferred luminance ratio (desk/paper) was 0.4, although it decreased slightly with higher illuminances. This ratio should be treated as approximate at best. Other studies have produced different preferred surround/task area luminance ratios, ranging from 0.1 to 1 depending on the specific situation (Rea et al., 1990). The median surround/task luminance ratio for these studies is 0.4. Given that white paper has a reflectance of about 0.75, this implies a desired desk reflectance of

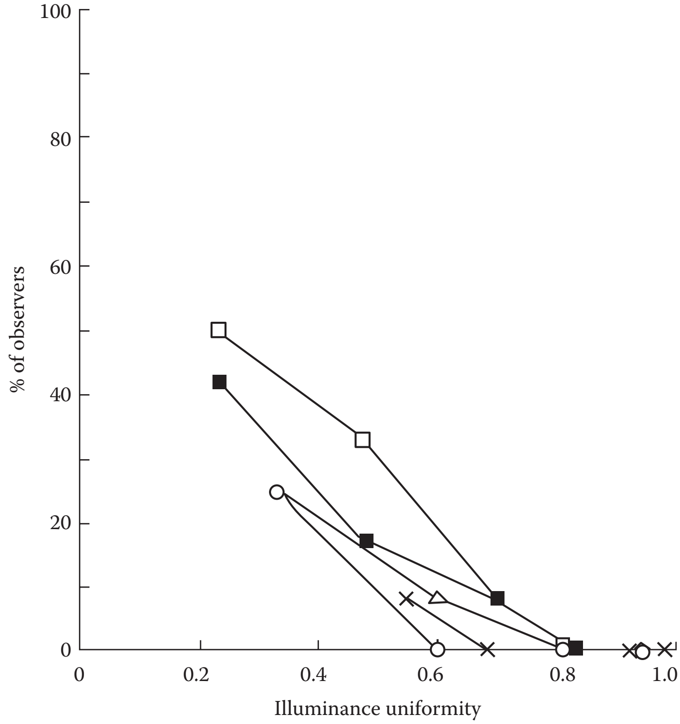


FIGURE 5.2 The percentage of observers' rating the evenness of lighting on the task as unacceptable plotted against illuminance uniformity across the task, for four tasks that required the use of the whole desk (□), half of the desk (○ and Δ), the centre of the desk (×) and for an empty desk (■). Uniformity is expressed as the ratio of the minimum to the maximum illuminance on the task. (After Slater, A.I. and Boyce, P.R., *Lighting Res. Technol.*, 22, 165, 1990.)

about 0.3. If a reflectance of this order is not possible with an existing desk, then the old-fashioned blotter sometimes provides a convenient way to provide the desired reflectance for the surround to the work.

One other aspect of uniformity that is important is when it is necessary to move the point of fixation from a low-luminance surface to a high-luminance surface and back again, repeatedly, such as might happen when looking between a computer screen and a piece of paper. Wibom and Carlsson (1987) examined this question with a field survey of almost 400 workers undertaking such work. Figure 5.3 shows the reported mean eye-discomfort score (a combination of eight reported symptoms of eye discomfort weighted according to the frequency and intensity of symptoms) for 281 women working at such a task for more than 5 h a day, plotted against the luminance ratio of the paper source document and the screen. It can be seen that a luminance ratio of greater than about 15:1 produces a marked increase in eye discomfort.

Clearly, the uniformity criteria that appear in lighting recommendations should be treated as guidance rather than matters of life or death. Complete uniformity of luminance is bad for vision, but the visual system is very tolerant of variations in

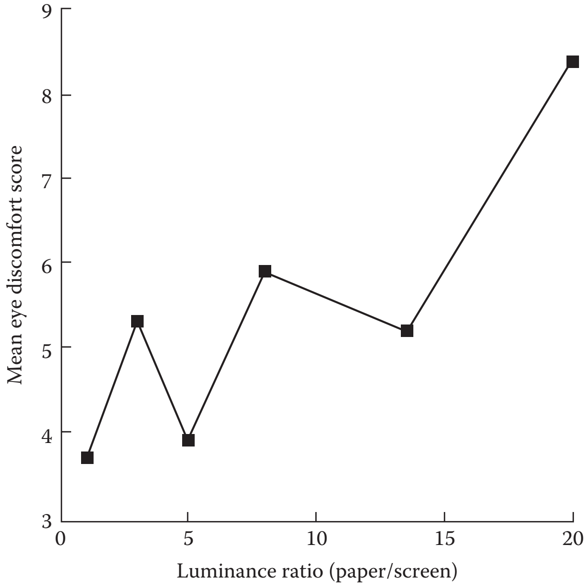


FIGURE 5.3 The mean eye-discomfort score given by women working for several hours between documents and a computer screen, plotted against the ratio of the luminances of the paper and the screen. (After Wibom, R.I. and Carlsson, W., Work at visual display terminals among office employees: Visual ergonomics and lighting, in Knave, B. and Wideback, P.G. (eds.), *Work with Display Units*, Vol. 86, North Holland, Amsterdam, the Netherlands, 1987.)

luminance in the visual scene; indeed, it is such variations that make seeing possible. But different degrees of uniformity are desirable in different locations. The most uniform illumination is required in the immediate task area. If task areas are scattered throughout a space, as in a multi-person office, and may move around over time, for example, when the office is rearranged, then a high level of illuminance uniformity is necessary over the whole working plane. If a working area is stable in location, then away from the working area, a greater degree of illuminance non-uniformity will be tolerated and may even be valued for the interest it gives to a space (see Section 6.3).

Given that uniform illumination is desirable for the task area, it is important to note that illuminance uniformity measured as a minimum/average ratio is not the complete story. It is also necessary to consider where the minimum and maximum illuminances occur and the rate of change of illuminance between them. A sudden change in illuminance across the task area, as may occur when the shadow of a shelf is cast onto the pages of a book, will always be considered uncomfortable.

All the aforementioned has been associated with the lighting of work, particularly office work, where the purpose of the lighting is to extract information from a 2D surface. For 3D material, such as often occurs in industry, non-uniform illumination patterns are required to reveal the form and texture of the object. This approach is taken to extremes in the theatre and is widely used in retailing to produce dramatic displays and change people's reactions to the lit object (Mangum, 1998). Thus, as with all the other factors that can cause discomfort, whether a non-uniform illuminance distribution actually causes discomfort will depend on the context in which it occurs.

5.4.2 Glare

The discomfort that may be experienced when non-uniform illumination is used in the wrong context tends to build up over time. Glare is a much more extreme form of non-uniformity and is usually apparent immediately. When faced with a very high luminance in the visual field, the usual behaviour is to blink and look away or to shield the eyes from the source of high luminance. This behaviour can be taken as an indication that glare is present.

Vos (1999) has suggested eight different forms of glare. Of these eight, four occur rarely. One is flash blindness, which is a temporary state of complete bleaching of retinal photopigment caused by the sudden onset of an extremely bright light source, for example, a nuclear explosion. Another is paralyzing glare, so named for the phenomenon in which a person suddenly illuminated by a searchlight at night will tend to freeze briefly. Another is exposure to light bright enough to cause retinal damage (see Section 14.2). The last is distracting glare, produced by bright, flashing lights in the peripheral visual field, for example, lights on emergency vehicles at night. These are all special situations remote from conventional lighting, so they will not be discussed further.

The other four forms of glare are more commonly experienced. The first occurs when a large part of the visual field is too bright. This is called dazzle or saturation glare. This is painful, and the behavioural response is to shield the eyes in some way, by wearing low-transmittance glasses or shields that restrict the view of the outside world by means of slits. Such devices are used in such diverse settings as the beaches of California and the icy wastes of the Arctic. Despite the differences in culture and lifestyle of the people who inhabit such places, the need to shield the eyes from large areas of very high luminance is common. Saturation glare occurs rarely indoors. It is much more common outdoors. It is probably a spasm of the iris sphincter that causes the sensation of pain (Lebensohn, 1951; Vos, 2003).

Saturation glare occurs when the large part of the visual field is at a high luminance for a long time. Another form of glare commonly experienced is adaptation glare. This occurs when the visual system is exposed to a sudden, large increase in luminance of the whole visual field, for example, on exiting a long road tunnel into sunlight. The perception of glare is due to the visual system being oversensitive because it is adapted to the relative darkness of the tunnel while being suddenly exposed to the brightness of sunlight. Adaptation glare is temporary in that the processes of visual adaptation will soon adjust the sensitivity of the visual system to the new conditions. It can be avoided altogether by designing lighting to give a transition zone of intermediate luminance between the tunnel interior and the open sky, the transition zone being long enough to allow the visual system time to adapt to the sunlight (IESNA, 2011b).

The other two forms of glare commonly experienced are essentially a matter of the range of luminances simultaneously present in the visual field. They are disability glare and discomfort glare.

5.4.2.1 Disability Glare

Disability glare, as its name implies, disables the visual system to some extent. This is caused by light scattered in the eye (Vos, 2003). The scattered light forms a luminous veil over the retinal image of adjacent parts of the scene. This has two effects. First, it reduces the luminance contrasts of the retinal image which will reduce the visibility of the scene. Second, the increased retinal illumination reduces threshold contrast which will increase visibility. Almost always, the first effect dominates the second (Patterson et al., 2012).

The amount of disability glare can be measured by comparing the visibility of an object seen in the presence of the glare source with the visibility of the same object seen through a uniform luminous veil. When the visibilities are the same, the luminance of the veil is a measure of the amount of disability glare produced by the glare source and is called the equivalent veiling luminance. Numerous studies have led to several different empirical methods to predict the equivalent veiling luminance (Holladay, 1926; Stiles, 1930; Stiles and Crawford, 1937). Based on this work, an equation has been developed to predict the equivalent veiling luminance from directly measurable variables. It is

$$L_v = 10\sum E_n \Theta_n^{-2}$$

where

L_v is the equivalent veiling luminance (cd/m^2)
E_n is the illuminance at the eye from the *n*th glare source (lx)
Θ_n is the angle between the line of sight and the *n*th glare source (degrees)

The effect of the equivalent veiling luminance on the luminance contrast of the object can be estimated by adding it to the luminance of both the object and the immediate background (see Section 2.4.1.1 for luminance contrast formulae).

The formula above is adequate for glare sources between about 1° and 30° from the line of sight and for young people. However, a series of modifications of the formula have been proposed to extend the range over which accurate predictions can be made from 0.1° to 100°, for age ranges up to 80 years and for eye iris colour (Vos, 1999; CIE, 2002b). Age is important because as the eye ages, the amount of scatter in the eye increases (see Section 13.2). Iris colour only becomes important at angles greater than about 30°, but above this limit, people with blue eyes experience more disability glare than people with brown eyes and non-Caucasian eyes.

Disability glare can be associated with point sources and large-area sources. The disability glare formulae can be applied directly to point sources, but for large-area sources, the area has to be broken into small elements and the overall effect integrated (Adrian and Eberbach, 1969; Adrian, 1976). Disability glare from point sources is experienced most frequently on the roads at night when facing an oncoming vehicle (see Section 10.2.5), although it can also occur during daytime when the sun is close to the required line of sight. As for disability glare from an extended source, this can occur outside when approaching a road tunnel during daytime. Then, the sky above the tunnel entrance can act as a glare source. It can also occur indoors when a bright sky is visible through a window.

5.4.2.2 Discomfort Glare

Disability glare is well understood. It has an effect on visual capabilities that can be measured with conventional psychophysical procedures and a plausible mechanism, light scatter in the eye. Discomfort glare is not well understood. It is said to be occurring when people complain about visual discomfort in the presence of bright light sources, luminaires or windows. There is no proven cause for discomfort glare, although suggestions have been made ranging from fluctuations in pupil size (Fry and King, 1975) through distraction (Lynes, 1977) to muscle tension around the eye (Berman et al., 1994a). The separation between disability and discomfort glare should not be taken to mean that disability glare does not cause visual discomfort nor that discomfort glare does not diminish the capabilities of the visual system. Whenever disability glare makes what needs to be seen more difficult to see, complaints of discomfort are likely to occur. As for the disabling effect of what is conventionally called discomfort glare, the failure to find any effects of visual capabilities is probably more a matter of measurement sensitivity than anything else. In essence, these two forms of glare, disability glare and discomfort glare, are simply two different reactions to the same stimulus pattern, namely, a wide variation of luminance across the visual field. When considering the likelihood of glare occurring for a given lighting situation, it is wise to consider both disability and discomfort glare.

Discomfort glare from small sources seen indoors, such as light sources and luminaires, has been studied for more than 60 years, starting with Luckiesh and Guth (1949) continuing through Hopkinson (1963), Bodmann et al. (1966), Einhorn (1969), Manabe (1976), Fischer (1991) and Eble-Hankins and Waters (2004), to mention only some. The outcome of this work has been a plethora of different national systems for predicting the degree of discomfort produced by different electric lighting situations. Today, there are really only two systems in widespread use. One is the visual comfort probability (VCP) system used in North America. VCP is based on the work of Guth (1963). For a single glare source, the formula for glare sensation is

$$\text{Glare sensation} = M = \frac{(0.50 L_s \times Q)}{(P \times F^{0.44})}$$

where

L_s is the luminance of the glare source (cd/m^2)

$Q = (20.4W_s + 1.52W_s^{0.2} - 0.075)$, where W_s is the solid angle subtended at the eye by the glare source (steradians)

P is an index of the position of the glare source with respect to the line of sight (Guth position index)

F is the average luminance of the field of view, including the glare source (cd/m^2)

The glare sensation produced by a number of glare sources is summed to form the discomfort glare rating (DGR) using the formula

$$\text{DGR} = (\Sigma M_n)^a$$

where $a = n^{-0.0914}$, n is the number of glare sources.

The DGR values are then converted to the VCP, which is simply the percentage of people who would be expected to find the conditions represented by the DGR acceptable. Luminaire manufacturers in North America use the VCP system to produce tabular estimates of the level of discomfort glare produced by a regular array of their luminaires for a range of standard interiors. The VCP system is based on empirical relations derived from a variety of experiments. It has been concluded that differences of 5% or less are not significant. In other words, it is only if two lighting systems differ in VCP by more than 5% that there is a basis for judging that there is a difference in discomfort glare between them.

The other discomfort glare prediction system in widespread use is the unified glare rating (UGR) system (Sorensen, 1987; CIE, 2002b). UGR represents a compromise between several national discomfort glare prediction systems. These systems all use a formula to calculate the glare sensation produced by an array of luminaires. The formulae are different in different systems but, for a single small glare source, they all have the following form:

$$\text{Glare sensation} = \frac{(L_s^a \cdot \omega_s^b)}{(L_b^c \cdot p^d)}$$

where

L_s is the luminance of the glare source (cd/m^2)
ω_s is the solid angle subtended at the eye by the glare source (steradians)
L_b is the luminance of the background (cd/m^2)
p is the deviation of the glare source from the line of sight
a, b, c and d are exponents that differ between systems

The form of the formula indicates the effect of the different components. Increasing the luminance of the glare source, increasing the solid angle subtended by the glare source, decreasing the luminance of the background and decreasing the deviation of the glare source from the line of sight will all increase the glare sensation. Changes of each component in the opposite direction will decrease the glare sensation. In principle, it is assumed that these four components are independent but, in practice, they interact. For example, consider the effect of lowering the mounting height of a luminaire in a room, keeping everything else the same. Assuming the direction of view is horizontal along the length of the room, then lowering the mounting height reduces the deviation from the line of sight but it is also likely to change the luminance of the background and, depending on the shape and luminous intensity distribution of the luminaire, it may also change the angular size and the luminance of the luminaire. To what extent these changes amplify or compensate can only be determined by applying the full equation.

The UGR formula takes the form

$$\text{UGR} = 8\log_{10}\left(\frac{0.25}{L_b}\right)\sum\left(\frac{L_s^2\,\omega}{p^2}\right)$$

where

L_b is the background luminance (cd/m^2), excluding the contribution of the glare sources (this is numerically equal to the indirect illuminance on the plane of the observer's eye, divided by π)
L_s is the luminance of the glare source (cd/m^2)
ω is the solid angle subtended at the observer's eye by the glare source (steradians)
p is the Guth position index of the glare source

The use of the UGR system is restricted to glare sources subtending 0.0003–0.1 steradians at the eye, so it cannot be used for indirect lighting or windows. The output scale of the UGR system is based on the obsolete British glare index system, namely, 10 = just perceptible glare, 16 = just acceptable glare, 22 = just uncomfortable glare and 28 = just intolerable glare. The minimum perceptible difference in discomfort glare is one unit on this scale (Collins, 1962). Commission Internationale de l'Eclairage (CIE) has adopted the UGR formula for predicting discomfort glare from luminaires (CIE, 2002b) and has developed a method for luminaire manufacturers to create tables of UGR values for standard viewing conditions (CIE, 2010b). There have even been proposals for converting the UGR values to VCP values for North America (Sorensen, 1991), a step that would be sensible given the high correlation between UGR and VCP ($r = 0.82$) obtained from calculations of the discomfort glare experienced in a room lit by regular arrays of 30 different types of fluorescent luminaires, including both prismatic and parabolic types (Mistrick and Choi, 1999).

The existence of UGR should not be taken to mean that we know all we need to know to predict and hence control discomfort glare from luminaires. Unfortunately, there remain a number of questions of application that need answering. For real luminaires, there can be problems in determining the luminance and solid angle of the glare source. For example, many luminaires are not uniform in luminance, particularly where specular reflectors or a number of low-light-output light sources, such as light emitting diodes (LEDs), are used. This makes it difficult to determine the glare source area and hence the solid angle. As for glare source luminance, the conventional method of calculation is to divide the luminaire luminous intensity in a given direction by the projected area of the luminaire in the same direction. If the area of the glare source is ambiguous, then the glare source luminance must be ambiguous also. Even if the glare source area is defined, it must be doubted if the resulting average luminance is the true measure of the glare source luminance for non-uniform luminance luminaires (Waters et al., 1995). CIE (2002b) offers some advice on how to deal with such luminaires.

There are questions about glare source size even when the luminance is uniform. Einhorn (1991) pointed out that all the glare control systems in use predict intolerable glare for very small sources, such as it may occur when bare lamps are used in chandeliers, yet these are tolerated very well. Likewise, there is problem with large sources because then the area of the glare source is large enough to interact with the adaptation luminance. CIE (2002b) has recommended a simple classification of size whereby small sources have areas less than 0.005 m^2 and large sources have areas greater than 1.5 m^2. Paul and Einhorn (1999) have shown that discomfort glare for small sources more than 5° off-axis is determined by the luminous intensity in the direction of the eye, not by the luminance of the source; and the UGR formula can be made applicable to such small glare sources by replacing the summed term $(L_s^2\,\omega)$ in the formula with $(200\ I^2/R^2)$ where I is the luminous intensity in the direction of the eye (cd) and R the distance from the source to the eye (m). For large sources, CIE (2002b) has recommended a transition formula for use with luminaires having areas just greater than 1.5 m^2 up to really large luminaires. The formula is

$$\mathrm{GGR} = \mathrm{UGR} + \left(1.18 - \frac{0.18}{\mathrm{CC}}\right) \cdot 8 \log \left(2.55 \frac{\left(1 + (E_d/220)\right)}{\left(1 + (E_d/E_i)\right)}\right)$$

where

CC is the ceiling coverage equal to A_0/A_1, where A_0 is the projected area of the glare source towards the nadir (m^2) and A_1 is the area lit by one glare source (m^2) = the room area/number of glare sources

E_d is the direct illuminance at the eye from the glare source (lx)

E_i is the indirect illuminance at the eye (lx)

The same GGR and UGR values represent the same level of discomfort glare. Where a luminous ceiling or uniform indirect lighting is used, CIE (2002b) proposes a limit on the average illuminance provided. Specifically, if a UGR value of 13 is desired, then the average illuminance provided should not exceed 300 lx; if UGR = 16, the average illuminance should not exceed 600 lx; and if UGR = 19, the average illuminance should not exceed 1000 lx.

Another factor to be considered is the effect of the luminance of the immediate surround to the glare source. In his original formulation of the glare sensation, Hopkinson (1963) included a fifth term for the immediate surround luminance. He found that an immediate surround, intermediate in luminance between the glare source luminance and the background luminance, produced a marked reduction in glare sensation. None of the glare prediction systems consider the immediate surround, although there is certainly evidence that both the luminance and colour of the immediate surround influence the perception of discomfort glare (Sweater-Hickcox et al., 2013).

Finally, there is a question about the impact of the deviation from the line of sight. Clear (2013) compared the original measurements of position factor (Luckiesh and Guth, 1949) with the more recent results of Kim et al. (2009). The two sets of data do not agree well.

Given all these uncertainties, it would not be surprising if UGR failed to accurately predict peoples' perceptions of discomfort. Akashi et al. (1996) examined the relationship between mean subjective ratings of discomfort glare of 61 observers (5 experts and 56 non-experts in lighting) and the calculated UGR values for the same view in a simulated office using 10 simple, bright-sided luminaires to deliver a number of different luminous intensity distributions. The correlation coefficient between the

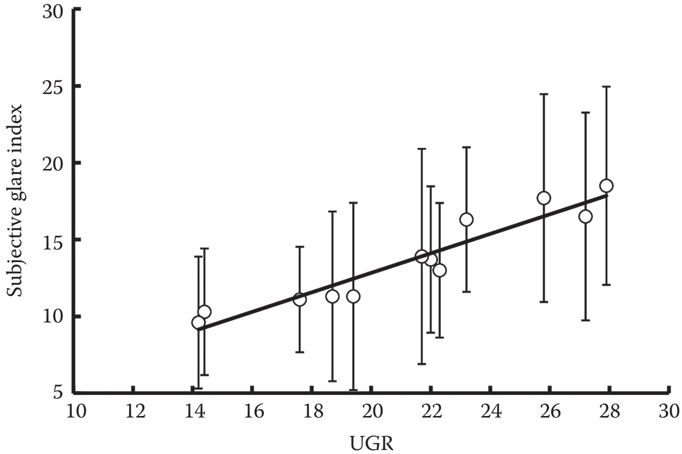


FIGURE 5.4 The mean subjective glare indices and associated standard deviations for observers' ratings of discomfort glare in a room lit in different ways plotted against the UGR values for the same view in the same room. Note the large individual differences in glare ratings revealed by the large standard deviations. (After Akashi, Y. et al., *Lighting Res. Technol.*, 28, 199, 1996.)

calculated UGR values and the mean subjective ratings of discomfort glare expressed on the same discomfort glare scale was 0.95. Figure 5.4 shows the high correlation, but what can also be seen is that there is a strong bias such that the mean subjective indices consistently indicated less discomfort glare than predicted by the UGR values. There are a number of possible reasons for this. Akashi et al. (1996) suggested that the problem lies in the way the contributions of multiple luminaires are combined by simple addition. Another possibility is that the majority of the observers were naïve about lighting, so may have been much less sensitive to glare than the lighting experts, a phenomenon reported by Hopkinson (1963). There is also the possibility that Japanese observers have different expectations about glare given the widespread use of bare fluorescent lamps in Japanese offices. While these are all possibilities, it is interesting to note that Cai and Chung (2013) also found that UGR consistently overestimated the level of discomfort glare experienced by Chinese observers when looking along a room lit by luminaires with non-uniform luminance patterns. It might be that less bias would be found if similar measurements were made in Europe or North America, where bare lamps are rarely used in offices. It would also be interesting to know how the relationship between UGR and mean subjective ratings would be altered by introducing more complex luminaire types and different room types into the data. Until this is done, a provisional conclusion is that UGR is the best system currently available for predicting peoples' perceptions of discomfort glare from small sources in interiors and includes a large safety margin within its criteria.

While UGR has been developed primarily for indoor luminaires, a parallel course has been followed for discomfort glare from large-area light sources such as windows. Work at Cornell University in the United States and the Building Research Station in the United Kingdom (Hopkinson, 1963) led to the development of the daylight glare index (DGI). This is expressed as an equation of the form

$$\text{DGI} = \frac{10\log S0.478\left(L_s^{1.6}W^{0.8}\right)}{\left(L_b + \left(0.07w^{0.5}L_s\right)\right)}$$

where

L_s is the luminance of the glare source (cd/m^2)

Ω is the solid angular subtense of the source at the eye of the observer modified for the effect of the position of the observer in relation to the source (sr) (Petherbridge and Longmore, 1954)

L_b is the luminance of the background (cd/m^2)

ω is the solid angular subtense of the source at the observer's eye (sr)

The denominator in the DGI formula includes both the size and the luminance of the source reflecting the fact that for large sources, light from the source affects the state of adaptation of the visual system. The output of the model is given on a scale similar to that given by UGR but with slightly different values, namely, 28 = just intolerable glare, 24 = just uncomfortable glare, 20 = just acceptable glare and 16 = just perceptible glare.

Fisekis et al. (2003) have shown a good correlation between DGI and subjective evaluations of glare from a window with an extensive view of the sky. However, Inoue and Itoh (1989) revealed that DGI does not behave as expected when the glare source covers the whole visual field. This led Tokura et al. (1996) to try another approach. They collected data from 240 observers looking at a simulated window in 120 different luminous conditions. From the data collected, they developed a simple empirical formula for something called the predicted glare sensation vote (PGSV). The formula for the PGSV is

$$\text{PGSV} = 3.2\log L_s - 0.64\log w + (0.79\log w - 0.61)\log L_b$$

where

L_s is the source luminance (cd/m^2)

ω is the solid angle of the source at the eye of the observer (sr)

L_b is the luminance of the background (cd/m^2)

It should be noted that there is no term relating to the deviation from the line of sight in the PGSV formula because it is assumed the observer is looking directly at the window. The outcome scale of the PGSV is 0 = just perceptible glare, 1 = just acceptable glare, 2 = just comfortable glare and 3 = just intolerable glare. Iwata and Tokura (1998) showed that PGSV becomes independent of the background luminance when the glare source fills the visual field, as it should.

The basic data from which the DGI and the PGSV methods were developed were obtained using a simulated window of uniform luminance but real windows can have wide point-to-point variations in luminance. Wienold and Christoffersen (2006) used high dynamic range (HDR) photography for luminance measurement (Inanici, 2006) to record the luminance distributions seen through real windows.

They also collected data from 70 observers on the level of discomfort glare experienced. They found that the correlation coefficient between the DGI calculated from the luminance data and the subjective assessments was 0.75, meaning only 56% of the variance in discomfort glare ratings could be explained by DGI. This inspired them to use the collected data to develop a new glare prediction method called the daylight glare probability (DGP). The equation for DGP is

$$\mathrm{DGP} = c_1 \cdot E_\mathrm{v} + c_2 \cdot \left(\log \frac{\left(1 + \Sigma \left(L_\mathrm{s}^2 \cdot \omega\right)\right)}{\left(E_\mathrm{v}^{c_4} \cdot p\right)} \right) + c_3$$

where
- E_v is the vertical illuminance at the eye (lx)
- L_s is the luminance of an element of the glare source (cd/m^2)
- ω is the solid angle subtended at the eye by the element of the glare source (sr)
- p is the position index of the element of the glare source
- c_1, c_2 and c_3 are constants

What is interesting about this formula is the presence of a simple part, the vertical illuminance at the eye, which ignores all the structure of the luminances in the window, and the more conventional part that considers the contribution from each element of the window. Not surprisingly, given that the DGP method was developed from the data collected, Wienold and Christoffersen (2006) found that the correlation coefficient between DGP and the collected subjective glare ratings was 0.97.

While the development of these methods for quantifying discomfort glare from windows suggests an increasing level of sophistication in measurement, another study has suggested that the problem of identifying the level of discomfort glare expected from a window involves much more than measurement. Tuaycharoen and Tregenza (2007) considered how the nature of the view seen through a window might affect the level of discomfort glare. Figure 5.5 shows individuals' assessments of discomfort glare when looking out of a window plotted against the calculated DGI for no view, where the window was fitted with a diffusing screen; a poor view of a concrete wall; and a good view consisting of housing and trees. The subjective assessment is called the glare response vote and is expressed on a scale matching the DGI scale with 16 = just perceptible glare, 20 = just acceptable glare, 24 = just uncomfortable and 28 = just intolerable glare. From Figure 5.5, it is clear that the same window can produce different perceptions of discomfort glare depending on the view seen through it; the better the view, the less the level of discomfort glare, and this effect is not small. It would be interesting to know if a similar effect occurs with luminaires, such as chandeliers, where the luminaire is an object of interest in itself.

By now, it should be apparent that discomfort glare from luminaires and windows has been the subject of considerable research effort, yet there is still a whiff of alchemy surrounding the subject. Like gold, discomfort caused by high luminances in the visual field is real but trying to predict discomfort accurately from the base

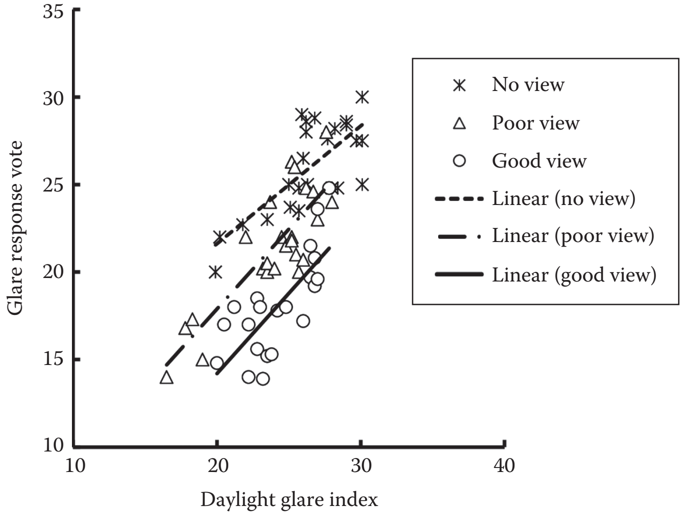


FIGURE 5.5 Glare response votes plotted against the calculated DGI for observers looking out of a window with different views. Also shown are the three linear regression lines through the data for each view. The three views shown are no view, in which the window was covered by a diffusing screen; a poor view of a concrete wall; and a good view of housing and trees. (After Tuaycharoen, N. and Tregenza, P.R., *Lighting Res. Technol.*, 39, 185, 2007.)

metal of physical measurements alone is inevitably imprecise. Partly, this is because there is no established physiological or perceptual mechanism for discomfort glare. Until a plausible mechanism is identified, the study of discomfort glare is likely to remain a matter of developing new empirical relationships as new technology and new design trends throw up unexpected discomfort glare problems. Even if a physiological or perceptual mechanism was to be identified, there would still be the fundamental fact that discomfort glare involves a psychological element in the form of the different criteria used by individuals, a fact that may explain the very large individual differences in discomfort glare perception found in many studies (Stone and Harker, 1973; Akashi et al., 1996). There is also the point that discomfort glare varies widely within the same space depending on the viewing position and direction of regard (Ashdown, 2005). However, technology may make this last point irrelevant. Using HDR imaging, it is now possible to rapidly collect large amounts of luminance data (Inanici, 2006). Further, visualization software now makes rapid calculation of UGR and DGP for many different viewing positions possible (Jakubiec and Reinhart, 2012). Whether or not such calculations are worthwhile when the underlying formulae are subject to so much uncertainty remains an open question.

Finally, it is worth noting that while attention has mainly been focused on the discomfort caused by indoor luminaires and windows, others have been working on methods to predict discomfort glare from vehicle headlights (see Section 10.2.5) and from outdoor lighting (see Section 11.6). Despite its difficulties and ambiguities, discomfort glare is clearly a topic that attracts researchers.

5.4.2.3 Overhead Glare

The Guth position indices for deviations vertically above the horizontal line of sight are usually limited to less than 53°, it being assumed that there is no sensation of glare at greater angles. However, it has been shown that given sufficient luminance, discomfort can be experienced from a luminaire at much higher angles even when the luminaire is then outside the field of view (Ngai and Boyce, 2000; Boyce et al., 2003a). The reason why a luminaire overhead but outside the field of view can cause discomfort is that it produces high luminances on elements surrounding the eyes such as the eyebrows, nose, cheeks and any glasses that are worn. Further, these high luminances shift every time the head is moved causing distraction. The luminance above which overhead glare is found to occur is about 16,500 cd/m^2, a value that is easily exceeded by some light sources.

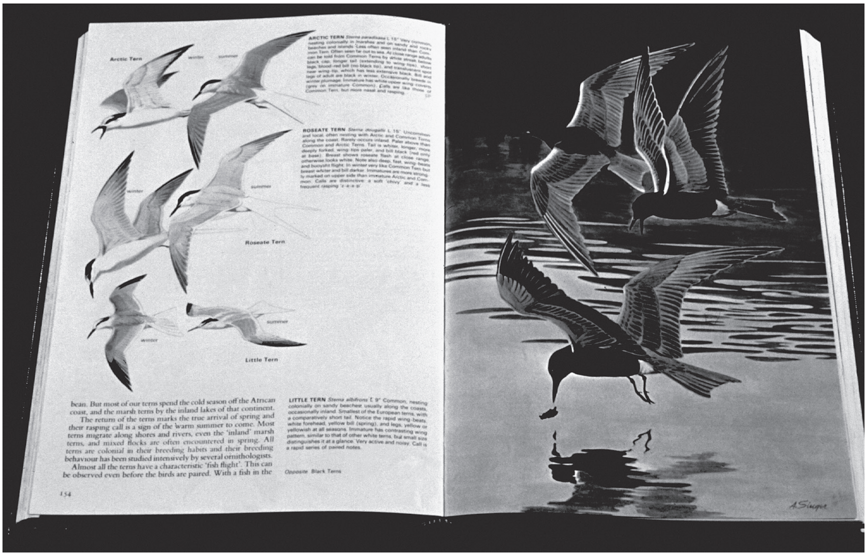
5.4.3 Veiling Reflections

Veiling reflections are luminous reflections from specular or semimatte surfaces that physically change the contrast of the visual task and therefore change the stimulus presented to the visual system (Figure 5.6). Veiling reflections and disability glare are similar in that both change the luminance contrast of the retinal image but differ in that veiling reflections change the luminance contrast of the task itself, while disability glare changes the luminance contrast of the retinal image of the task.

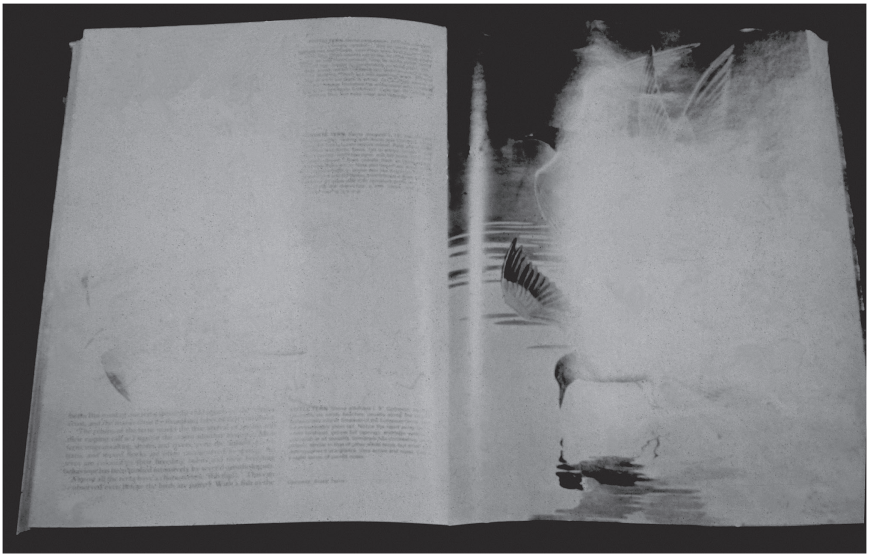
The two factors that determine the nature and magnitude of veiling reflections are the specularity of the surface being viewed and the geometry between the observer, the surface and any sources of high luminance. If the surface is a perfectly diffuse (Lambertian) reflector, no veiling reflections can occur because then the distribution of light reflected from the surface is independent of the direction from which the light is incident. If the surface has a specular reflection component, veiling reflections can occur. Veiling reflections occur at positions where the geometry between the observer, the surface and any sources of high luminance is such that the angle of incidence equals the angle of reflection and the reflection is in the direction from the surface to the eye of the observer.

The magnitude of veiling reflections can be quantified by the contrast rendering factor (CRF). The CRF of a surface at a specific location and viewed from a particular direction is the ratio of the luminance contrast of the object under the lighting of interest to the luminance contrast of the object under completely diffuse lighting. Completely diffuse lighting produces only weak veiling reflections so a CRF value close to unity is desirable if veiling reflections are to be avoided. Unfortunately, for simplicity, where sources of high luminance are surrounded by areas of low luminance, as is the case for many recessed, direct lighting installations, the magnitude of veiling reflections and hence the CRF can vary dramatically within the installation (Boyce, 1978). There is no such thing as a single value of CRF for a lighting installation. There is always a distribution of values.

The effect of veiling reflections on the luminance contrast of a specific target may be quantified by adding the luminance of the veiling reflection to the appropriate components in one of the luminance contrast formulae (see Section 2.4.1.1). What the appropriate components are depends on the reflection properties of the material



(a)



(b)

FIGURE 5.6 A glossy book (a) without and (b) with veiling reflections.

being viewed. For glossy ink writing on matte paper, the luminance of the veiling reflections should only be added to the luminance of the ink. For a glossy magazine page or a computer screen, where there is a specularly reflecting transparent coating over the whole surface, veiling reflections occur over the whole surface. In this case, the luminance of the veiling reflections should be added to all terms in the luminance contrast formula.

The usual effect of adding the luminance of the veiling reflections to the luminance contrast formulae is to reduce the luminance contrast of the target. However, this is not always the case. For example, given a very specular black ink printed on matte white paper, it is possible for veiling reflections to increase the luminance of the ink so much that it becomes higher than the luminance of the paper, that is, the polarity of the print is reversed and luminance contrast starts to increase again. This will lead to an increase in the CRF, despite the fact that the strength of the veiling reflections is increasing. This possibility means that CRF values should be evaluated with care wherever the material consists of both specular and matte reflecting elements.

The extent to which changes in luminance contrast change visual performance can be estimated using the relative visual performance model (see Section 4.3.5) but the extent to which it causes discomfort is different. Bjorset and Frederiksen (1979) measured the acceptability of the contrast reduction produced by veiling reflections for a wide range of handwritten and printed materials. Figure 5.7 shows the percentage reduction in contrast that 90% of their subjects found acceptable, plotted against the contrast of the material when no veiling reflections occurred. It is apparent that 90% of the subjects accepted a contrast reduction of about 25% regardless of whether the materials had high- or low-luminance contrast in the absence of veiling reflections. This result suggests two conclusions. The first is that discomfort can occur whenever lighting interferes with the visibility of the task even if the reduction in visual performance is slight. The second is that weak veiling reflections are not

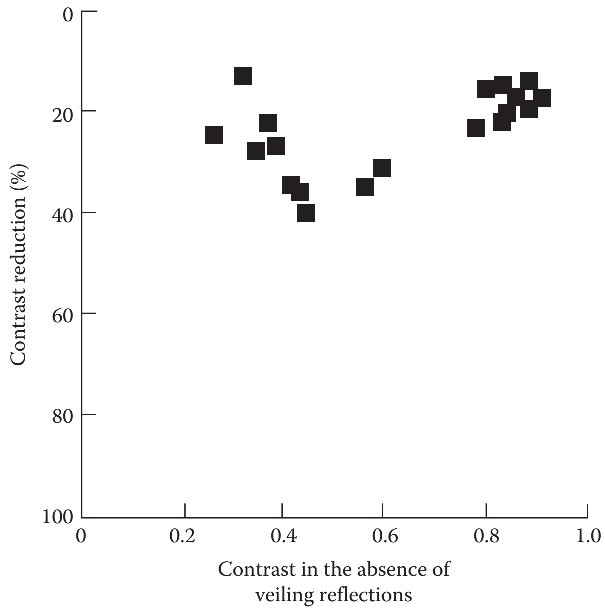


FIGURE 5.7 Percentage reduction in luminance contrast that 90% of observers found acceptable, plotted against the luminance contrast of the material when no veiling reflections occurred. (After Bjorset, H.H. and Frederiksen, E.A., A proposal for recommendations for the limitation of the contrast reduction in office lighting, *Proceedings of the CIE 19th Session*, Kyoto, Japan, CIE, Paris, France, 1979.)

critical for comfort, a conclusion supported by Reitmaier (1979), at least for pencil, pen and printed text on matte and moderately glossy paper. However, for very glossy papers, people were very sensitive to the presence of even slight veiling reflections, something that de Boer (1977) also found.

Although veiling reflections are usually considered a negative outcome of lighting that can cause discomfort, they can be used positively, but when they are, they are conventionally called highlights. Physically, veiling reflections and highlights are the same thing. Display lighting of specularly reflecting objects, such as jewellery, is all about producing highlights to reveal the specular nature of the surface.

5.4.4 Shadows

Shadows are cast when light coming from a particular direction is intercepted by an opaque object. If the object is big enough, the effect is to reduce the illuminance over a large area. This is typically the problem in industrial lighting where large pieces of machinery cast shadows in adjacent areas. The effect of these shadows can be overcome either by increasing the proportion of inter-reflected light by using high-reflectance surfaces or by providing local lighting in the shadowed area. If the object is smaller, the shadow can be cast over a meaningful area which, in turn, can cause perceptual confusion, particularly if the shadow moves. An example of this is the shadow of a hand cast on a document. This problem can also be reduced by increasing the inter-reflected light in the space or by providing local lighting that can be adjusted in position.

Although shadows can cause visual discomfort, it should be noted that they are also an essential element in revealing the form of 3D objects. Techniques of display lighting are based around the idea of creating highlights and shadows to change the perceived form of the object being displayed. Many lighting designers insist that the distribution of shadows is as important as the distribution of light in achieving an attractive and meaningful visual environment (Lam, 1977; Tregenza and Loe, 2014).

The number and nature of shadows produced by a lighting installation depends on the size and number of light sources and the extent to which light is inter-reflected around the space. The strongest shadow is produced from a single point source in a black room. Weak shadows are produced when the light sources are large in area and the degree of inter-reflection is high.

5.4.5 Flicker

Virtually, all electric light sources that operate from an AC supply produce regular fluctuations in the amount and spectrum of light emitted. When these fluctuations become visible, they are called flicker. A lighting installation that produces flicker will be almost universally disliked, unless it is being used for entertainment and then only when exposure is short. For some people, exposure to flicker can be a health hazard (see Section 14.3.3).

The main factors that determine whether a fluctuation in light output will be visible are the frequency and percentage modulation of the fluctuation at the eye, the proportion of the visual field over which the fluctuation occurs and the adaptation luminance. The higher is the adaptation luminance and the larger is the area, the more likely it is that a given frequency and percentage modulation fluctuation will be seen. Temporal modulation transfer functions (see Section 2.4.4) can be used to predict whether a given frequency and percentage modulation of fluctuation occurring over a large area will be visible at a given adaptation luminance. It is important to appreciate that there are wide individual differences in sensitivity to flicker (Hopkinson and Collins, 1970). This, together with the fact that electrical signals associated with flicker can be detected in the retina, even when there is no visible flicker (Berman et al., 1991), implies that a clear safety margin is necessary to avoid discomfort from flicker.

The probability that a lighting installation will be seen to produce flicker depends on the stability of the electricity supply and the type of light source used. Sources that rely on incandescence to produce light are relatively insensitive to high-frequency oscillations in the electricity supply because the thermal inertia of the filament limits the percentage modulation, but they are very sensitive to slow fluctuations in supply voltage because these affect the temperature of the filament. Where the local electricity network has equipment attached to it that can impose sudden large loads, for example, the motors of a steel rolling mill, slow fluctuations in supply voltage are likely and, in consequence, so are fluctuations in light output of incandescent light sources. These can be minimized by using a voltage regulator between the electricity supply and the light source.

Sources that rely on an electrical discharge to produce light are less sensitive to supply voltage fluctuations than incandescent lamps because the electricity supply is filtered through the control gear. It is the output of this control gear combined with the persistence of any phosphors used that determine whether a lighting installation using discharge lamps will produce flicker. Older-style electromagnetic control gear typically produces an output at the same frequency as the electricity supply frequency, that is, at 50 or 60 Hz, depending on the country, so the light output has a fundamental frequency of 100 or 120 Hz. Modern electronic control gear typically produces an output with a frequency of around 25–50 kHz. Given the time constants of the light-producing processes in most discharge lamps, this increase in supply frequency produces not only a higher frequency in light output but also a smaller percentage modulation in light output. Veitch and McColl (1995) found no difference in the levels of comfort produced by fluorescent lighting producing flicker at 120 Hz and in the range 20–60 kHz. However, the use of high-frequency control gear on fluorescent lamps has been associated with a reduction in the prevalence of headaches and eyestrain for people who experience these symptoms regularly (Wilkins et al., 1989).

With the increasing use of electronic control gear for discharge lamps, flicker had almost disappeared as a practical problem for lighting but the arrival of LEDs has reinvigorated concern. This is because such solid-state light sources have an inherently fast response time, of the order of nanoseconds, although this may be lengthened when a phosphor is used to create a white light source (see Section 1.7.3.9). Bullough et al. (2011a) examined the effects of flicker frequency and percentage modulation on the perception of flicker from an LED desk lamp used without any other lighting in the room. Figure 5.8 shows the percentage of observers who could

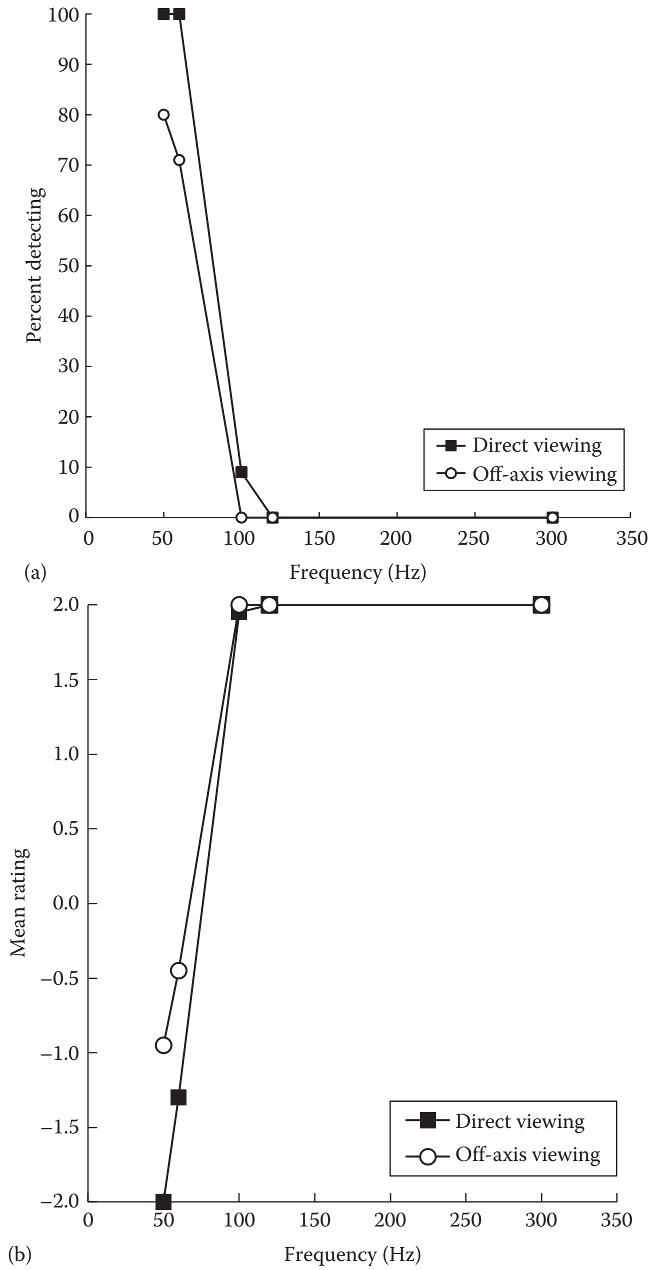


FIGURE 5.8 (a) The percentage of observers who could detect 100% modulation flicker at different frequencies when looking directly at the reflector of an LED desk lamp and 40° away from it and (b) the mean ratings of acceptability for observers who detected flicker. The acceptability ratings were made on a scale of −2 = very unacceptable, −1 = somewhat unacceptable, 0 = neither acceptable nor unacceptable, +1 = somewhat acceptable and +2 = very acceptable. (After Bullough, J.D. et al., *Lighting Res. Technol.*, 43, 337, 2011a.)

detect 100% modulation flicker when looking directly at the reflector of the LED desk lamp and 40° away from it and the percentage who, having detected flicker, found that level of flicker acceptable. It is clear that at 50 and 60 Hz, such flicker is easily detected and unacceptable but at 100 and 120 Hz, it is rarely seen and when it is, it is acceptable. A similar pattern was found when the question asked was about the level of comfort. Hundred percent modulation at 50 Hz was considered very uncomfortable; at 60 Hz, it was somewhat uncomfortable; but by 100 Hz, it was considered comfortable. This means that there is no inherent reason why LED light sources operating from a rectified AC supply should cause discomfort but as Ruskin said ‘There is nothing in the world that some man cannot make a little worse and sell a little cheaper, and he who considers price only is that man’s lawful prey’. This certainly applies to LED systems and may be why the IEEE is currently working on a standard for the flicker from solid-state lighting systems that may introduce new metrics for flicker. The proposed metrics are based on a truncated Fourier series so as to be able to deal with light output waveforms that contain multiple frequency components (Lehman et al., 2011).

All the aforementioned has been concerned with flicker seen directly but there is also a possibility for flicker to be seen indirectly via a stroboscopic effect. The most well-known example of this phenomenon is when a light source with 100% modulation is used to change the apparent movement of rotating machinery, making it appear stationary when it is actually moving. Another example is when a person spreads their fingers and waves them backwards and forwards under a light source. Measurements of this phenomenon, using a white wand rather than fingers, have shown that both frequency and percentage modulation affect the ability to detect flicker and that this can occur at frequencies up to 10,000 Hz (Bullough et al., 2012b). Although it was possible for some people to detect flicker in this way, acceptability was at a high level once the frequency exceeded 1000 Hz, even for 100% modulation (Figure 5.9).

Interestingly, a stroboscopic effect can also be seen without external movement. Given a high-percentage modulation from the light source and a large saccadic eye movement, a series of bright spots will be seen along the path taken by the saccade. This is known as a phantom array and can occur at frequencies up to 2 kHz (Roberts and Wilkins, 2013). Phantom arrays are rarely seen in lighted interiors, saccadic suppression increasing the threshold contrast and the high luminance of the background decreasing the actual contrast, but are more easily seen outside, at night, when the background is dark so the actual contrast is higher, for example, from vehicle LED rear lights. Indoors or outside, direct or indirect, the solution to flicker is to use light sources with a high-frequency and low-percentage modulation of fluctuation.

Although directly visible flicker occurring over a large area is almost always disturbing, localized directly visible flicker does have its uses. It is a potent means of attracting attention because peripheral vision is sensitive to changes in the retinal illumination pattern either in space or time. Localized flicker is widely used to attract attention to essential and nonessential information, such as the presence of emergency vehicles and the location of coupon dispensers in supermarkets.

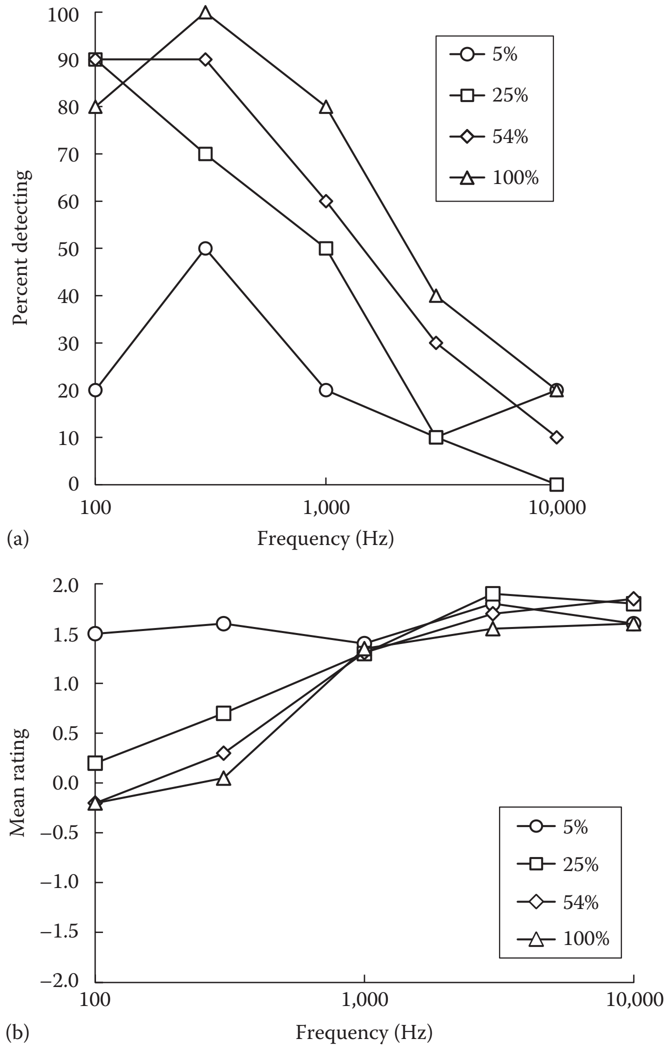


FIGURE 5.9 (a) The percentage of observers who could detect a stroboscopic effect when waving a white wand from side to side under an LED desk lamp plotted against frequency for different percentage modulations. (b) the mean acceptability ratings for those subjects who had detected a stroboscopic effect using a five-point scale: −2 = very unacceptable to +2 = very acceptable. (After Bullough, J.D. et al., *Lighting Res. Technol.*, 44, 477, 2012b.)

5.5 DISCOMFORT, PERFORMANCE AND BEHAVIOUR

While lighting conditions that make it difficult to achieve good visual performance will almost always be considered uncomfortable, lighting conditions that allow a high level of visual performance may also be considered uncomfortable. Figure 5.10 shows the mean detection speed of a group of 20–30-year-olds trying to find a specific two-digit number from 100 such numbers printed in black ink on grey paper and

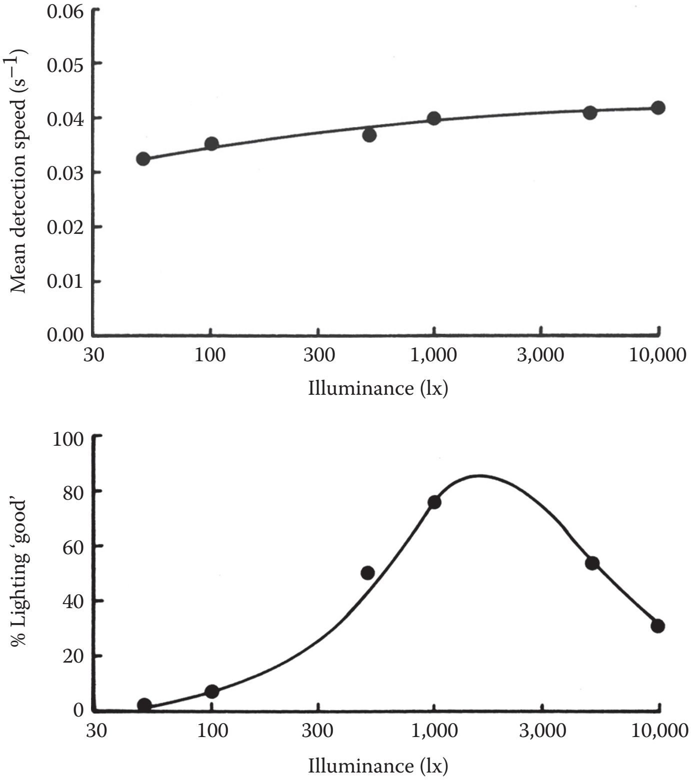


FIGURE 5.10 Mean detection speeds for locating a specified number among others at different illuminances and the percentage of subjects who consider the lighting good at each illuminance. (After Muck, E. and Bodmann, H.W., *Lichttechnik*, 13, 502, 1961.)

laid out at random on a table. Figure 5.10 also shows the percentage of the same group considering the lighting good (Muck and Bodmann, 1961). As might be expected, increasing the illuminance on the table increases mean detection speed and the percentage considering the lighting good. However, as the illuminance exceeds 2000 lx, the percentage considering the lighting good declines even though the mean detection speed continues to increase.

These results have three interesting implications. The first is that lighting conditions that are considered uncomfortable do not necessarily lead to a decrease in task performance. The reason for this lack of effect is probably motivation. In laboratory experiments, people are usually highly motivated to succeed and will try to ignore any discomfort. It must be doubted if the same degree of motivation occurs frequently outside the laboratory, in which case lighting that causes discomfort may lead to a decline in task performance. The important word here is may. There can be no doubt that motivation can affect task performance and little doubt that lighting conditions can affect motivation, but so do many other factors. These other influences ensure that while lighting may sometimes affect performance by changing motivation, it is unlikely to have any effect that is consistent across individuals or even across time with the same individual, until extreme conditions are reached.

The second implication is that to achieve a lighting installation that will be liked by the people who work under it, it is necessary to provide lighting that allows easy visual performance and avoids discomfort. This may not be as simple as it sounds because the visual performance component of task performance is determined solely by the capabilities of the visual system but visual comfort is linked to peoples' expectations. Any lighting installation that does not meet expectations may be considered uncomfortable even though visual performance is more than adequate and expectations can change over time.

The third is that as lighting conditions vary, perceptions of visual discomfort will be more sensitive to changes than task performance. This, in turn, implies that judgements of visual discomfort are the most effective way to determine the quality of a lighting installation, a conclusion that has also been reached by Roufs and Boschman (1991) for visual displays.

Finally, it is interesting to note that visual discomfort can have behavioural consequences when discomfort is severe. People are not stupid. If there is an obvious source of visual discomfort in the environment, people will act to remove it or diminish its effect. It is not uncommon to find pieces of paper taped to the windows of offices. The usual reason for this is to prevent the light from the early morning or afternoon sun falling directly on a display screen. Similarly, people will adjust vertical blinds during the day to prevent direct sunlight falling on their desks while preserving a view out (Maniccia et al., 1999). Also, given that veiling reflections can be diminished dramatically by changing the geometry between the source of high luminance, material and observer, it is common for people to tilt the material or move their heads to reduce veiling reflections (Rea et al., 1985a). The presence of behavioural modifications to the environment is a clear indication of visual discomfort occurring in their absence.

5.6 VISUAL DISCOMFORT AND LIGHTING QUALITY

Lighting designers frequently claim that what they deliver is lighting quality and it seems obvious that avoiding visual discomfort is an inherent part of lighting quality, but is that all there is to it? This question is difficult to be answered because there is no clear definition of lighting quality. Like pornography, we know it when we see it but what it is differs from one individual and culture to another. A number of different approaches to defining lighting quality have been suggested: from single-number photometric indices calibrated by subjective responses (Bean and Bell, 1992); to the results of a holistic design process based on lighting patterns (Loe and Rowlands, 1996); to the lighting conditions which have desirable impacts on task performance, health and behaviour (Veitch and Newsham, 1998b); to lighting which enhances the ability to discriminate detail, colour, form, texture and surface finishes without discomfort (Cuttle, 2008). The definition that seems most generally applicable is that lighting quality is given by the extent to which the installation meets the objectives and the constraints set by the client and the designer. Depending on the context, the objectives can include facilitating desirable outcomes, such as enhancing the performance of relevant tasks, creating specific impressions and generating a desired pattern of behaviour, as well as ensuring visual comfort. The constraints are usually the maximum allowed financial and power budgets, a maximum time for completion of the work and, sometimes, restrictions on the design approach to be used.

To many people, such a definition must be a disappointment. It is both mundane and obvious. It is not expressed in terms of photometric measures but rather in terms of the impact lighting has on more distant outcomes. There are three arguments in favour of such an outcome-based definition of lighting quality rather than any of the alternatives based directly on lighting variables. The first is that lighting is usually designed and installed as a means to an end, not as an end in itself, so the extent to which the end is achieved becomes the measure of success. The retailer does not care about lighting, *per se*, but only about lighting as a tool for increasing sales. The second is that what is desirable lighting depends very much on the context. Almost all the aspects of lighting that are considered undesirable in one context are attractive in another. The third is that there are many physical and psychological processes that can influence the perception of lighting quality (Veitch, 2001a,b). It is this inherent variability that makes a single, universally applicable recipe for good-quality lighting based on photometric quantities an unreal expectation.

So where does visual discomfort fit into lighting quality? A simple concept that offers a place for visual discomfort is that lighting installations can be divided into three classes of quality: the good, the bad and the indifferent. Bad-quality lighting is lighting that does not allow you to see what you need to see, quickly and easily and/or causes visual discomfort. Indifferent quality lighting is lighting that does allow you to see what you need to see quickly and easily and does not cause visual discomfort but does nothing to lift the spirit. Good-quality lighting is lighting that allows you to see what you need to see quickly and easily and does not cause visual discomfort but does raise the human spirit. On this scale, much of what constitutes current lighting practice falls into the class of indifferent lighting.

This in turn raises another question, what is it that causes lighting to be classified as good, bad or indifferent quality? The outcome-based definition of bad-quality lighting implies that such lighting occurs when it is inappropriate for what the visual system is being asked to do. For example, if a particular visual task involving specific visual size and contrast characteristics has to be performed, then lighting which makes the luminance contrast between the task and its background low, or the luminance contrast between irrelevant stimuli and their backgrounds high, will be considered bad lighting – the former making the visibility of the task poor and the latter causing distraction. Among the phenomena which can contribute to such effects are insufficient light, too much light, excessive non-uniformity, veiling reflections, shadows, flicker and disability and discomfort glare, that is, all the phenomena which we currently think of as being responsible for visual discomfort. Eliminating these phenomena will generally lead to indifferent lighting. This would not be a mean achievement. Indeed, it may be the best that can be expected from the use of guidelines and quantitative lighting criteria. It may be that once bad lighting is avoided, the difference between indifferent lighting and good lighting is a matter of context, fashion and opportunity. Context is important because what would be considered attractive lighting for an office seems unlikely to be so attractive in an intimate restaurant. Fashion is important because we often crave the new to provide interest and variety. There is no reason to suppose that lighting should be any different in this respect than most other aspects of life. As for opportunity, that is partly a matter of technology and of being in the right place at the right time. And what is the right place? An eminent lighting designer, J.M. Waldram, once said ‘If there is nothing worth looking at, there is nothing worth lighting’, so the right place is presumably a place which contains something worth looking at. Also, given that to be really good the lighting has to be matched in some way to the particular environment, each lighting solution would be specific and not generally applicable. This combination of fashion and specificity suggests that the conditions necessary for good lighting quality are liable to change over time and space and hence will not be amenable to determination by scientific methods. At the moment, good-quality lighting most frequently occurs at the conjunction of a talented architect and a creative lighting designer, neither of whom is given to slavishly following numerical lighting criteria.

But this is looking at current lighting practice through rose-tinted spectacles. Table 5.1 shows the percentage of office workers agreeing with statements about the lighting of their office. The data come from 1259 people working in 13 different offices in the northeastern region of the United States. The offices had lighting installations of different types and ages. The questionnaire used had been shown to be reliable and valid (Eklund and Boyce, 1996). From Table 5.1, it is clear that there is still a long way to go before visual discomfort at work is eliminated. Only 69% of the office workers agreed that the lighting of their offices was comfortable – yet it is possible to achieve higher values. Table 5.2 shows the percentage of temporary office workers who experienced a number of different types of lighting installation in a cubicled office for a day and considered the lighting comfortable (Boyce et al., 2006b). The regular array of recessed louvred fluorescent luminaires was used because it was

TABLE 5.1
Average Percentage of Office Workers Agreeing with a Statement about the Lighting of Their Offices

Statement	Average Percentage Agreeing
Overall, the lighting is comfortable.	69
The lighting is uncomfortably bright for the tasks I perform.	16
The lighting is uncomfortably dim for the tasks I perform.	14
The lighting is poorly distributed here.	25
The lighting causes deep shadows.	15
Reflections from the lighting hinder my work.	19
The light fixtures are too bright.	14
My skin is an unnatural tone under the lighting.	9
The lights flicker throughout the day.	4

Source: After Eklund, N.H. and Boyce, P.R., *J. Illum. Eng. Soc.*, 25, 25, 1996.
Note: The data were collected from 1259 people working in 13 different offices.

TABLE 5.2
Percentage of Temporary Office Workers Agreeing with Statements about Different Forms of Office Lighting

Statement	Regular Array of Recessed Louvred Luminaires	Regular Rows of Suspended Direct/Indirect Luminaires	Luminaires Centred over Workstations with Individual Control
Overall, the lighting is comfortable.	71	85	91
The lighting is uncomfortably bright for the task I perform.	33	21	11
The lighting is uncomfortably dim for the tasks I perform.	4	8	13
The lighting is poorly distributed here.	16	18	15
The lighting causes deep shadows.	12	10	7
Reflections from the lighting hinder my work.	29	17	21
The light fixtures are too bright.	38	20	19
My skin is an unnatural tone under the lighting.	22	13	30
The lights flicker throughout the day.	4	0	2

Source: After Boyce, P.R. et al., *Lighting Res. Technol.*, 38, 191, 2006b.

considered to be the most common approach to office lighting in North America. Similar to what was found in the earlier study, only 71% considered this lighting installation comfortable. The installation of regular rows of suspended direct/indirect fluorescent luminaires was considered to be best practice for office lighting as it produced the same illuminance on the workstation but brighter walls and ceiling with fewer shadows and less veiling reflection. The percentage considering the direct/indirect lighting comfortable was 85%. The ultimate in office lighting was provided by having suspended direct/indirect fluorescent luminaires centred over each cubicle and giving the occupant control of the direct component so that individuals could adjust the illuminances on their workstations. Ninety-one percent considered this lighting comfortable.

Tables 5.1 and 5.2 also suggest what the causes of discomfort are for the installations examined. For the older installations examined by Eklund and Boyce, (1996) (Table 5.1), the basic problems appear to be light distribution and veiling reflections. For the installations used in Boyce et al. (2006b), the situation is somewhat different (Table 5.2). For all three types of installation, insufficient light, shadows and flicker are little problem. However, too much light, luminaire brightness, veiling reflections and colour rendering of skin all occur as significant problems in different installation types. Clearly, current lighting practice could do better, but for that to happen, attention will have to be given to all the aspects of lighting that cause discomfort, not just to illuminance.

5.7 SUMMARY

Where lighting is intended to facilitate the extraction of information from the visual environment, there are four situations in which visual discomfort is likely to occur and are as follows:

1. Visual task difficulty, in which the lighting makes the required information difficult to extract
2. Under- or overstimulation, in which the visual environment is such that it presents too little or too much information
3. Distraction, in which the observer's attention is drawn to objects that do not contain the information being sought
4. Perceptual confusion, in which the pattern of illuminance can be confused with the pattern of reflectance in the visual environment

The occurrence of visual discomfort is made manifest by the occurrence of red, itchy eyes, headaches and aches and pains associated with poor posture. The aspects of lighting that can cause visual discomfort are too little light, too much light, too much variation in illuminance between and across working surfaces, disability glare, discomfort glare, veiling reflections, shadows and flicker. Whether any or all of these aspects of lighting do cause visual discomfort depends on the context in which the lighting is installed. Virtually, all of them can be used positively in the right context. For example, veiling reflections are undesirable when they mask what you want to see, but when they are used to reveal the nature of the specular surface of a silver plate, and are called highlights, they are just what is wanted.

There is a lot of guidance published on how to avoid visual discomfort in common working interiors (SLL, 2009; IESNA, 2011a). Some of this advice is qualitative, for example, for avoiding shadows and veiling reflections, while other advice is quantitative, for example, limiting values for discomfort glare and illuminance non-uniformity. The existence of quantitative recommendations should not be taken to mean that exact compliance is necessary. The quantitative guidance for providing visual comfort should be treated as approximate at best.

Eliminating visual discomfort is not a recipe for good-quality lighting. Rather, it is a recipe for eliminating bad-quality lighting and replacing it with indifferent lighting. This would be no small achievement. Surveys of occupants' opinions about common office lighting practice indicate that only about 70% find the lighting comfortable. There is clearly a long way to go before the blessings of even indifferent quality lighting are available to all.

6 Lighting and the Perception of Spaces and Objects

6.1 INTRODUCTION

The route from a luminous environment to the perception of that environment by a human being is long and convoluted. As formulated by Cuttle (2008),

> The *luminous environment* generates the *retinal image* which is the stimulus for the *process of vision* which provides information to enable the *visual perception process* to recognize the objects and surfaces that form the visual basis for the *perceived environment*.

From this formulation, it should be apparent that the photometric and colorimetric quantities described in Chapter 1 and that are used to quantify the luminous environment are effectively measures of the stimulus to the visual system. The response of the visual system, in terms of the perception, is related to the stimulus received but not to the stimulus alone. This is for three reasons. First, perception depends on the state of adaptation of the visual system. Different states of adaptation have different capabilities. For example, when the visual system is in the mesopic state, its ability to discriminate colour is reduced from what it is in the photopic state, and when it is in the scotopic state, it has no ability to discriminate colour at all. Also, as the state of adaptation changes, so does the sensitivity of the visual system to light. Consider a vehicle headlight seen by day and by night. The headlight has the same luminance under both conditions, but it will be seen as much brighter by night than by day because of the increased sensitivity to light produced by adaptation of the visual system to the generally lower luminances at night.

Second, the stimulus for perception in the real world is rarely a single item, seen in isolation. Rather it is a complex structure in which objects are seen against different backgrounds and in different patterns. Variations in the background can alter the perception of objects seen against that background. Figure 6.1 is a demonstration of this. It shows a grey annulus, the background of which is either black or white. The reflectance of the grey annulus is the same throughout, but the grey seen against the black background is perceived as lighter than the grey seen against the white background. This effect is enhanced if a dividing edge is placed along the black/white border, thereby demonstrating that perception is also influenced by the way the luminous environment is organized into patterns. Purves and Beau Lotto (2003) provide many illustrations demonstrating the impact of the surroundings on the perceived

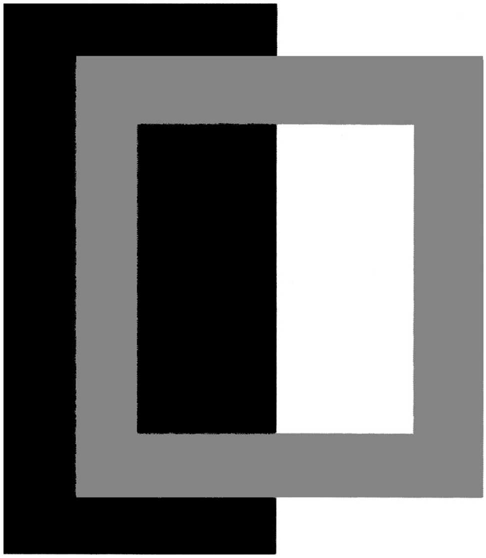


FIGURE 6.1 A demonstration of the interaction between elements of a scene affecting perception. The two parts of the square annulus have the same reflectance but appear to be of different lightnesses because of the influence of the background. The effect is enhanced by placing a dividing edge across the annulus at the black/white boundary of the background.

colour and lightness of objects. It is the interactive aspects of perception, where the perception of each element in the luminous environment is dependent on other elements that make the link between the luminous environment and the perception of that environment so variable.

Third, perception is guided by our present knowledge and past experience of the luminous environment, and these determine the assumptions we make about objects and the ways they are usually lit. Figure 2.30 provides an illustration of this effect, the dents and dings changing places depending on the orientation of the figure.

There can be no denying that perception of the luminous environment is a complex process and that knowledge of the luminous environment alone is not enough to make an accurate prediction of how that environment will be perceived. Nonetheless, the luminous environment is the starting point of perception and lighting can be used to change the luminous environment. This chapter is devoted to describing the impact of lighting conditions on both simple and higher-order perceptions.

6.2 SIMPLE PERCEPTIONS

Given the number of factors that may intervene in the relationship between the stimulus provided by a luminous environment and the resulting perception, it is necessary to first consider the extent to which different people have the same perception in the same luminous environment. The first thing to say is that there is stability of perception. The occurrence of the perceptual constancies (see Section 2.5.1) and the existence of visual illusions that are seen by everybody is evidence that perception can be stable, even if it is distorted. The question then becomes under what conditions does stable perception occur. There is no quantitative answer to this question, but there is a statement of principle that can be made. This is that the greatest stability of perception will be obtained when there is least opportunity for factors such as knowledge and past experience to intervene and where the perception is closely linked to the operation of the visual system. Thus, it is relatively easy to show a stable relationship between the luminance of a small disc in a dark field and the brightness of the disc and the change in brightness of the disc when the spectrum of the light is changed. Least stability of perception will occur when there are many opportunities for knowledge and past experience to intervene or when the operating characteristics of the visual system have only a minor impact on the perception. Thus, the impact of light distribution on the perception of the spaciousness of an interior is much less stable than the perception of brightness because spaciousness is associated with factors other than the luminous environment, such as the amount and arrangement of furniture in the space. Simple perceptions, such as the brightness and colourfulness of a stimulus, are more likely to be stable than higher-order perceptions such as the spaciousness and attractiveness.

6.2.1 Lightness

As discussed in Section 2.5.2, surfaces that are seen by having light reflected from them have a perception of lightness, related to their reflectance. Sources that emit light have a perception of brightness, related to their luminance. Lynes (1971) discusses the conditions in which lightness constancy is maintained, that is, over which the perception of the lightness of a surface will remain stable. He concludes that diffuse, uniform lighting, which is what is provided in most commercial and industrial interiors, ensures lightness constancy. Nonetheless, it should be appreciated that lightness constancy is not perfect. Over a wide range of illuminances, the lightness of a surface changes (see Section 2.5.1).

6.2.2 Brightness

6.2.2.1 Luminance and Brightness

The study of the basic relationship between luminance and brightness has a long history, starting with Fechner (1860) and coming to fruition in the work of Stevens (1961). Over a number of years, Stevens was able to show that there was a consistent relationship between stimulus intensity and a number of different perceptions, such as loudness, smell, heaviness and taste, as well as brightness. The relationship between luminance and brightness was studied using a uniform, self-luminous target whose brightness was to be judged, surrounded by a uniform luminance field. The perception of brightness was quantified using a direct magnitude estimation procedure in which the observer was told to award a number to the first luminance presented. If the number given was 10, then the observer was instructed that if the next stimulus was seen as twice as bright as the first, then it should be given the value 20, but if it was one tenth as bright as the first, it should be given the value of 1. In this way, a ratio scale of brightness perception was constructed. Another method used was cross-modality matching, in which observers adjusted the magnitude on one perceptual dimension until it matched the perceived intensity of the stimulus from another dimension; for example, they adjusted the force exerted on a handgrip until it appeared to match the brightness of the stimulus. Both measurement methods showed that the link between brightness and luminance is not linear but rather follows a power law of the following form:

$$B = kL^n$$

where
- B is the brightness magnitude
- k is a constant
- L is the luminance of the stimulus (cd/m^2)
- n is an exponent

Another consistent finding was that there are large differences between individuals in the value of the exponent, although whether this is due to some inherent difference in the sensitivity of the individuals' visual systems or to differences in the way the measurement method was used by different individuals is unclear. It was also found that the exponent of the power law was influenced by the size and luminance of the surround field, relative to the luminance of the target whose brightness was being judged, as well as the state of adaptation of the observer's visual system and the colour of the stimulus and/or surround. Marsden (1969) reports that for small targets subtending less than 2°, in dim surrounds, the exponents found by different experimenters range from 0.23 to 0.31.

Bodmann and La Toison (1994) report a general model of brightness/luminance that covers a range of background luminances. Specifically, they use the model of Haubner (1977) which is

$$B = cL_t^n - B_0 \quad \text{and} \quad B_0 = c(s_0 + s_1 L_u^n)$$

where
- B is the brightness magnitude, set to $B = 100$ at $L_t = L_u = 300$ cd/m^2
- L_t is the luminance of a test field (cd/m^2)
- L_u is the luminance of a uniform background (cd/m^2)
- n is an exponent equal to 0.31
- c, s_0 and s_1 are constants

For a 2° test field, $c = 22.969$, $s_0 = 0.07186$ and $s_1 = 0.24481$.

When L_t is much greater than L_u, this equation reduces to Stevens's power law. As L_u increases, the brightness of the test patch decreases, ultimately reaching zero, that is, blackness.

While such studies in a simple context have generated a basic understanding of the relationship between brightness and luminance, there must always remain some doubt about their relevance to the complex luminance patterns typical of those found in lighted interiors. Fortunately, Marsden (1970) examined the perception of brightness for a real-size room furnished with both opaque reflecting objects and translucent self-luminous objects. The range of luminances available from surfaces within the room was 3–4000 cd/m^2, a range typical of surface luminances in an interior. His studies have shown that the perceived brightness of any single surface in the room increases with luminance according to a power law with an exponent of 0.35 but that the brightness of a number of surfaces seen simultaneously follows a power law with an exponent of 0.6. These relationships can be used to estimate the change in brightness of surfaces in an interior following a change in luminance by assuming that the brightest surface in the room has a brightness given by

$$B_{max} = L_{max}^{0.35}$$

Then, other surfaces in the room will have a brightness given by

$$B = aL^{0.6}, \quad \text{where} \quad a = \frac{B_{max}}{L_{max}^{0.6}} = L_{max}^{-0.25}$$

This simple system gives estimates of the average perception of brightness for a group of observers but underestimates the brightness of highly saturated coloured surfaces and overestimates the brightness of translucent surfaces. It is important to appreciate that these relationships are approximate at best and should be used for guidance only. There are large individual differences in the perception of brightness.

6.2.2.2 Light Distribution and Brightness

It is implicit in the finding that the constant in the expression linking the luminance of a surface in a room to its perceived brightness is determined by the maximum luminance of any surface in the room that the overall perception of brightness in a room is influenced by the distribution of light in the room. This has implications for the perception of room brightness produced by different types of lighting installation. Direct lighting is lighting in which all the light is emitted from the luminaire downwards to the working plane. Indirect lighting is its opposite, all the light leaving the luminaire being emitted upwards so that light only reaches the working plane after reflection from one of the room surfaces, usually the ceiling. Houser et al. (2002) have demonstrated that a room lit by indirect lighting is perceived as brighter than the same room lit by direct lighting when both installations deliver the same illuminance to the working plane (Figure 6.2). This implies that both the walls and ceiling contribute to the overall room brightness.

Loe et al. (1994) have also examined the effect of light distribution on the perception of room brightness. Using 18 different lighting installations in a conference room, they found that the perception of brightness was determined not only by the range of luminances present in the space but also by the location of those luminances, some locations being more important than others. Specifically, it appeared that the luminances within a 40° vertical zone about a horizontal line of sight were most important in determining the perception of brightness, an average luminance of

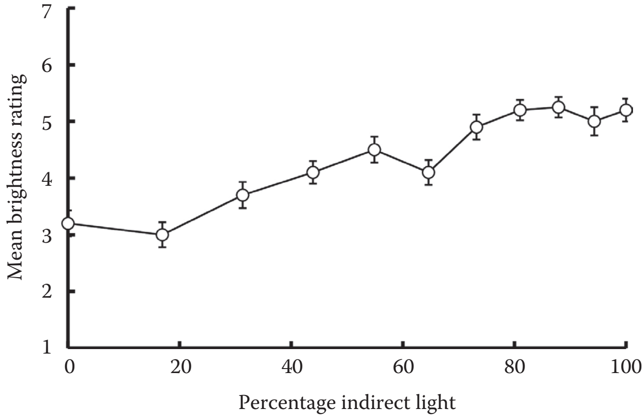


FIGURE 6.2 Mean and standard error of the rating of overall brightness of a room plotted against the percentage of light emitted from the luminaire above a horizontal plane through the luminaire, that is, indirect lighting. The brightness rating scale ranges from 1 = dim to 7 = bright. The illuminance on the horizontal work plane was fixed at 538 lx for all light distributions. (From Houser, K.W. et al., *Lighting Res. Technol.*, 34, 243, 2002.)

at least 30 cd/m^2 being required for the room not to appear dim. For someone looking down a room, a 40° band emphasizes the luminance of the walls relative to the luminances of the ceiling and floor. In a similar study, Loe et al. (2000) found that an average luminance of 40 cd/m^2 for a 40° vertical and 90° horizontal zone about a horizontal line of sight was required to reach the boundary between the rooms looking dim and bright. Such consistency is encouraging, but limiting the area over which luminances are averaged to a 40° vertical by 90° horizontal band is not supported by the results of Miller et al. (1995). They conducted a similar study using a direct lighting, with and without wall washing, and indirect lighting, for a range of illuminances on the working plane. Attempts to relate the acceptability of the lighting of the room to the luminance of different surfaces were most successful when both wall and ceiling luminances were considered. Figure 6.3 shows the relationship between the acceptability of the lighting and a metric called volumetric brightness, that is, the average luminance of ceiling and walls. The weakness of this study and those of Loe et al. (1994, 2000), as admitted by the authors, was that all the participants were either experts in lighting design or studying lighting and hence might be expected to have prejudices about the different lighting types. It would have been interesting to know how a group of people naive in lighting would have responded to the same installations. For the moment, it will have to be sufficient to note that both studies justify the use of an indirect component of lighting to enhance the perception of brightness in a room or, if that is not possible, the use of wall washing where direct lighting puts little light on the walls.

Despite the uncertainty about the relative importance of different room surfaces, there can be no doubt that the distribution of light in a room can alter the perception of brightness of the room. Shepherd et al. (1989, 1992) confirmed this in a series of studies devoted to the perception of what might be called the opposite of brightness, gloom. Using a word list from which subjects had to choose the words that applied

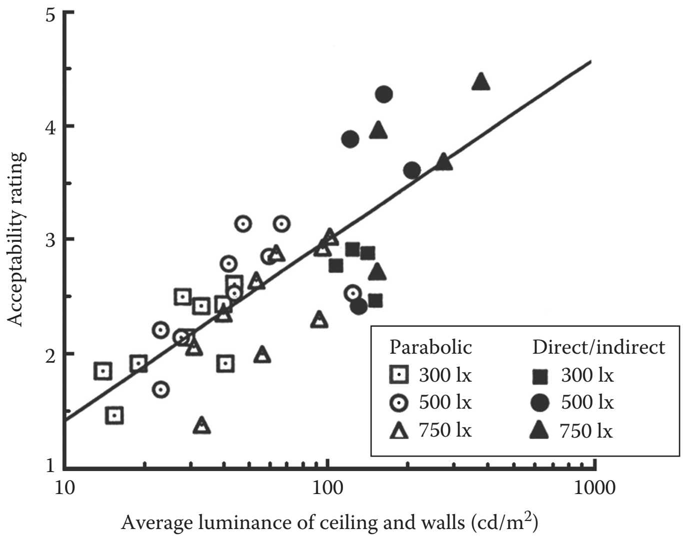


FIGURE 6.3 Mean acceptability ratings (1 = completely unacceptable, 3 = barely acceptable, 5 = completely acceptable) for different lighting installations plotted against the average luminance of ceiling and walls produced by the installations. The installations used recessed parabolic fluorescent luminaires or suspended direct/indirect fluorescent luminaires, to produce 300, 500 or 750 lx on the working plane, in the same office setting. (After Miller, N.J. et al., An approach to the measurement of lighting quality, *Proceedings of the IESNA Annual Conference*, New York, IESNA, New York, 1995.)

to the space, they showed that the perception of gloom was associated with several different situations. Specifically, Shepherd et al. (1992) concluded that a perception of gloom could be produced by

- Low surround luminances, irrespective of task illuminance
- Conditions in which small details in the periphery are obscured
- High task illuminances with low luminances on the peripheral surfaces
- Adaptation luminances in the mesopic range

Again, these results imply that direct lighting that leaves the walls poorly illuminated will result in a perception of gloom, implying that using wall washing to increase the illuminance on the walls will increase the perception of brightness. Interestingly, the same conditions produced the same perception of gloom for students of lighting and architecture and for members of the general public, which suggests that the concern about the use of subjects experienced in lighting may be unwarranted.

The mixed use of luminance and illuminance in these conclusions raises another interesting question. Is it possible to make a room with low-reflectance surfaces, such as mahogany-panelled walls, look bright? The answer to this question is positive, but only when the amount and distribution of light can be understood (Cuttle, 2004). As explained in Section 2.5.1, provided the amount and distribution of light in the room can be understood, the perceptual system can split the pattern of luminances received at the retina into a pattern of reflectances and a pattern of illuminances. Then, provided brightness in this situation can be taken to relate to the perception of the amount of light in the room, which is what Ishida and Ogiuchi (2002) have shown, a room with low-reflectance surfaces can indeed be perceived as bright.

6.2.2.3 Luminaire Luminance and Brightness

Another aspect of lighting practice that can affect the perception of brightness is the design of luminaires. The question of interest here is whether high-luminance elements in a luminaire can alter the perception of brightness in a space or do they simply make the lighting installation uncomfortable by causing discomfort glare (see Section 5.4.2.2).

Bernecker and Mier (1985) examined the effect of changing the luminance of an element of fixed size in an indirect lighting luminaire. They found that increasing the luminance of the element led to a perception of greater room brightness. Akashi et al. (2000) followed up this work but included the area subtended at the eye by the luminous element and the background luminance as variables. To measure brightness, an observer looked at two, one fifth scale model rooms, furnished with a desk and a valence luminaire. The only difference between the two rooms was that in one room, the test room, the valence luminaire had a slot forming a luminous element cut in it. The illuminance on the desk in the test room, and hence the background luminance, was set to a fixed level. The subject then adjusted the amount of light in the other room until the overall brightness of the two rooms looked the same. The ratio of the illuminances on the desks in the two rooms when they appeared to be of equal brightness was taken as a measure of the impact of the luminous element in the luminaire. If the ratio was greater than unity, it meant that the effect of the luminous element was to increase the perception of brightness. The mean illuminance ratios for the small number of subjects used, for three different background luminances, five different luminous slot sizes and five different luminous slot luminances, ranged from about 0.8 to 1.3. These values imply that the presence of a luminous element in a luminaire can both enhance and diminish the perception of room brightness, depending on the conditions. The pattern of illuminance ratios showed that reducing the size of the luminous element and increasing its luminance will tend to enhance the perception of brightness. However, increasing the luminance too much or making the luminous element too large will lead to a perception of glare which makes the rest of the room look less bright, while having too little luminance relative to the background produces little effect. It should be clear that using a luminous element in a luminaire to enhance room brightness is something that needs to be handled with care.

6.2.2.4 Light Spectrum and Brightness

There are a number of reasons why light spectrum can be expected to have an effect on the perception of brightness, over and above any effect of room surface luminances and luminaire luminance. To appreciate this, it is simply necessary to remember that luminance is based on the spectral sensitivity of the fovea, containing mainly medium- and long-wavelength sensitive cones, in photopic conditions, and measured using flicker photometry, a method that emphasizes the magnocellular channel. Therefore, increasing the size of the area being examined so the peripheral retina is included will introduce the effect of short-wavelength cones and, possibly, the intrinsically photosensitive retinal ganglion cells (Berman, 2008; Vidovszky-Nemeth and Schanda, 2012). In addition, increasing the size of the area being examined will reduce the impact of the macula that covers the central part of the retina. Decreasing the adaptation luminance so that the visual system moves from the photopic to the mesopic state will change the active photoreceptors from cones alone to both rods and cones. Viewing a steadily presented scene will ensure both the achromatic and colour channels of the visual system are active. All these effects will be applicable to an abstract object consisting of a disc of light and more complicated scenes such as the rooms and streets that make up the visual environment for most people.

The fact that the spectral content of the light reaching the eye influences the perception of brightness has been known for many years and goes under the name of the Helmholtz–Kohlrausch effect (Wyszecki and Stiles, 1982). This effect is simply that when two fields of different colours but the same luminance are placed side by side, the one with the greater colour saturation will appear brighter. The Helmholtz–Kohlrausch effect is different for different colours. Specifically, the effect is much weaker for a perception of yellow than for a perception of red, green or blue (Padgham and Saunders, 1975).

This pattern is also evident in the work of Ware and Cowan (1983). These authors took data from 29 different studies involving heterochromatic brightness matching for small self-luminous fields (less than 2°) and derived an empirical formula to calculate conversion factors for determining the relative brightness of colours. For colours where the y chromaticity coordinate is greater than 0.02, the conversion factor can be calculated from the following equation:

$$C = 0.256 - 0.184y - 2.527xy + 4.656x^3y + 4.657xy^4$$

where

C is the conversion factor

x, y are Commission Internationale de l'Eclairage (CIE) 1931 chromaticity coordinates of the stimulus

To rank order a number of light sources for brightness, at the same luminance or even at different luminances, all that is required is to obtain the sums of

$$\log(L) + C$$

where

L is the luminance (cd/m^2)

C is the conversion factor

For the same luminance, the light source with the highest value of the conversion factor will appear brightest. Figure 6.4 shows the iso-conversion factor contours based on the Ware and Cowan equation. The iso-conversion factor contours of Ware and Cowan, and those of other authors with a more theoretical approach (Nakano et al., 1999), have an interesting implication for lighting practice. The conversion factors

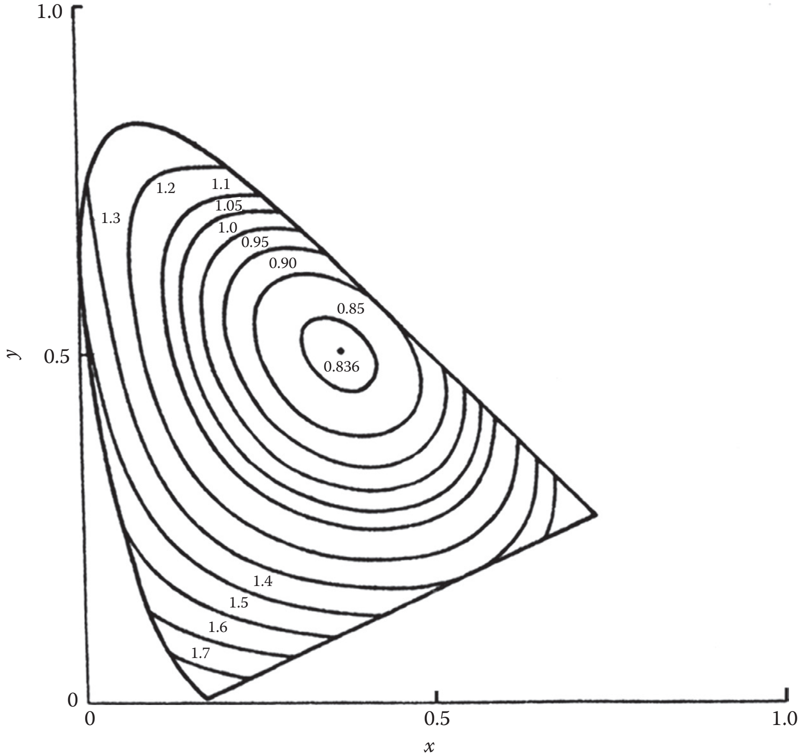


FIGURE 6.4 Iso-conversion factor contours plotted on the CIE 1931 (*x*,*y*) chromaticity diagram. (After Ware, C. and Cowan, W.B., Specification of heterochromatic brightness matches: A conversion factor for calculating luminances of small stimuli which are equal in brightness, Technical Report 26055, National Research Council Canada, Ottawa, Ontario, Canada, 1983.)

increase with greater saturation of the colour apart from towards the yellow part of the CIE 1931 (*x*,*y*) chromaticity diagram. This implies that, for the same luminance, nominally white light sources with a higher correlated colour temperature (CCT) should be seen as brighter than those with lower CCTs, a conclusion also reached by Harrington (1954). One doubt about this conclusion is that the data on which it is based are for small discs of light and so, presumably, are due to the action of the chromatic channels, but not to photoreceptors other than the medium- and long-wavelength sensitive cones. This means the data are of value for signal lights but may be of little relevance for a real room, for two reasons. First, lighting in a real room presents a large visual field and so stimulates all the photoreceptors in the retina. Second, the luminance pattern of the room surfaces can be perceptually separated into illuminance and reflectance patterns, the brightness being related to the former rather than the latter.

One study that addresses the effect of light spectrum on brightness in real rooms is that of Boyce et al. (2002). This study used two offices identically furnished and lit to the same illuminance by fluorescent lamps with different CCTs and CIE general colour rendering indices (CRIs), housed in luminaires with similar light distributions. Specifically, one light source had a CCT of 6500 K and a CRI of 98 and the other had a CCT of 3500 K and a CRI of 82, that is, the two light sources had very different light spectra. For the same distribution of illuminances in the offices, the light source with the CCT of 6500 K and a CRI of 98 produced a perception of greater brightness than the other. Another study in the same area was that of Boyce and Cuttle (1990), who had 15 observers carry out a colour discrimination task in a small office and then give an assessment of the lighting. The office was lit by fluorescent lamps with virtually the same CRI value (CRI = 82–85) but very different CCTs (2700–6300 K), producing four different illuminances on the desk (30, 90, 225 and 600 lx) from the same luminaire. The major factor in determining the impression given by the lighting was the illuminance. Increasing the illuminance made the lighting of the office appear more pleasant, more comfortable, warmer, more uniform, less hazy, less oppressive, less dim and less hostile. In this study, the different CCTs had virtually no effect on the observer's impression of the lighting of the room. Similarly, Hu et al. (2006) used a forced choice method and an illuminance adjustment method to examine the relative brightness of two identically furnished rooms lit by fluorescent light sources with different CCTs. In neither case was the difference in CCT found to influence the brightness of the room. However, Berman et al. (1990) had subjects view a spectrally neutral interior lit by pairs of light sources with different light spectra but the same chromaticity and hence with the same CCT, each for a 5 s period. The results showed that subjects consistently perceived a difference in brightness for two light sources that were in opposition to the photopic luminances. These results imply that, in large visual fields, brightness perceptions can be different for light sources with different light spectra, even when those light spectra lead to the same chromaticity and hence the same CCT.

The results of these studies serve to emphasize the limitations of some of the widely used single-number metrics of light source colour properties, such as CCT and CRI. For perception, it is the difference in light spectra that matters and hence the differences in the mixture of wavelengths that reach the eye either directly or indirectly after reflection from the room surfaces. Given that single-number metrics are inadequate for describing the effect of light source spectrum on the brightness of a room, it is possible to go to the other extreme and embrace the complexity of colour appearance models (CIE, 2004c; Fairchild, 2005). These models require detailed information about the photometric and colorimetric values for the surfaces and objects in room and the light source being used, but they can be applied to predict the brightness and colourfulness of those surfaces and objects. Unfortunately, the effort required to apply such models is likely to be difficult to justify for anything other than the most expensive and prestigious lighting designs. This leaves a large gap for researchers to exploit in the search for metrics able to predict room brightness more accurately than is possible with CCT and CRI and with less effort than is required by the colour appearance models.

Another question that needs to be addressed is 'What is the relative effect of light spectrum directly on brightness and indirectly through its effect on the saturation of surface colours in a space?' This question can be answered by considering the magnitude of the effect in achromatic interiors and interiors filled with surface colours. Berman et al. (1990) had observers looking at a uniform, spectrally-neutral interior and found large differences in brightness for different light sources. This implies that the effect of light spectrum on brightness is present even in the absence of surface colours. But does the presence of surface colours enhance the effect? Boyce and Cuttle (1990) measured the effect of introducing a range of colours, in the form of fruit and flowers, on the perception of an achromatic room and a room decorated in one colour. It was found that introducing fruit and flowers into the rooms increased the perception of brightness at the same illuminance. Against this are the findings of others (Fotios and Cheal, 2011a; Bullough et al., 2011b) that having coloured objects in the scene makes little difference to the effect of different light spectra on the perception of overall brightness of the scene, although this is what would be expected if scene brightness is basically concerned with the perception of the amount of light in the space.

Yet another factor to be considered is the time available for chromatic adaptation. Based on a review of studies using different presentation methods, Fotios (2006) concludes that chromatic adaptation reduces the impact of differences in light spectrum on brightness but does not eliminate it. This means that when the designer considers the importance of light spectrum for brightness, it is necessary to ask if it is the initial impression or the impression after chromatic adaptation has taken place that matters.

Obviously, there is still much to learn about how and why different light spectra affect the perception of brightness of interiors but that they do is no longer a matter of argument (Vidovszky-Nemeth and Schanda, 2012). Also not a matter of argument is the fact that light spectrum has an effect on the perception of brightness in mesopic conditions such as those that are produced by many forms of exterior lighting. In mesopic conditions, both rod and cone photoreceptors are active. It is well known that rod and cone photoreceptors interact in highly non-linear ways to affect brightness perception (Wyszecki and Stiles, 1982) and that rods and short-wavelength cones are not involved in luminance. Fotios and Cheal (2007a) had observers compare the brightness of two booths: one lit by high-pressure sodium (HPS) lighting and one by metal halide (MH) lighting to 7.5 lx, the two being viewed simultaneously. The mean ratio of illuminances for equal brightness was MH/HPS = 0.73. Fotios and Cheal (2010) have made similar measurements for a single booth lit by HPS and MH lighting to 7.5 lx but seen sequentially. The illuminance ratio for equal brightness using this method was MH/HPS = 0.74.

Rea et al. (2009a) describe a field measurement of brightness for a section of road lit by either a HPS or a MH luminaire, the two luminaires having a similar luminous intensity distribution. Beneath each luminaire was placed a poster board showing pictures of people and scenery together with a visual acuity chart. The observer stood midway between these two luminaires so that by looking in opposite directions, two forms of lighting could be seen. Three experiments were carried out. In the first, the vertical illuminances on the poster boards were adjusted mechanically to be either 5 or 15 lx. The observers were asked to state under which of the two scenes did the street and the objects look brighter. Six combinations of illuminance and light source type were examined. In the second experiment, the same procedure was used but three vertical illuminances were used: 7.5, 10 and 15 lx. In the third experiment, the observers were placed in a booth and viewed the two scenes through apertures fitted with neutral density filters. This enabled the differences in vertical illuminance to be more finely adjusted. Figure 6.5 shows the percentage of observers

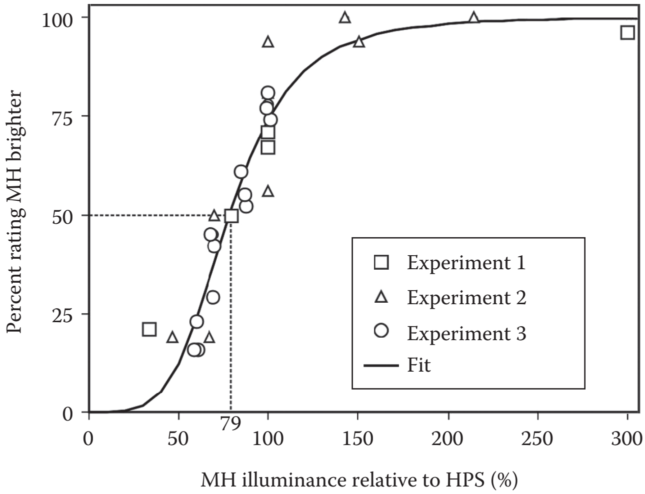


FIGURE 6.5 The percentage of observers rating the MH lighting as brighter than the HPS lighting plotted against the illuminance provided by the MH lighting as a percentage of the illuminance provided by the HPS lighting. (After Rea, M.S. et al., *Lighting Res. Technol.*, 41, 297, 2009a.)

stating that the MH lighting was brighter than the HPS lighting plotted against the vertical illuminance of the MH lighting relative to the vertical illuminance of the HPS lighting, for all three experiments. It can be seen that for equal brightness, that is, when 50%, say the MH lighting is brighter, and 50%, say the HPS lighting is brighter, the MH needs only to provide 79% of the illuminance of the HPS lighting. The agreement between this study using a real road and the results of Fotios and Cheal (2007a, 2010) using a simple booth is encouraging.

Following from these field measurements, Rea et al. (2011) have returned to the laboratory to develop a provisional model of outdoor scene brightness that could be applied to any light source. The model constructed is based on the spectral sensitivity data for peripheral vision measured by Wooten et al. (1975). The model takes the following form:

$$B(\lambda) = V(\lambda) + gS(\lambda)$$

where

$B(\lambda)$ is the brightness
$V(\lambda)$ is the photopic luminous efficiency
$S(\lambda)$ is the luminous efficiency of the short-wavelength cone
g is a weighting factor that changes with cone adaptation level

The fact that g is greater than zero implies that the activity of the short-wavelength cones is important for the perception of brightness for large fields. The fact that g decreases as the cone adaptation level decreases means that the relative contribution of short-wavelength cones diminishes as the cone adaptation level decreases.

A series of small experiments using different light sources showed that appropriate values of g were 1.5 when the illuminance on the ground of a model scene was 2 lx and 2.5 when the illuminance was 20 lx, two illuminances that cover the range normally used for outdoor lighting. There is a limit to how far this equation can be extrapolated. At very low adaptation luminances, rod photoreceptors dominate brightness perception. The suggested adaptation luminance where this begins to happen is 0.01 cd/m^2, corresponding to an illuminance on a road of about 0.2 lx. As for high adaptation luminances, how well this model fits brightness perceptions for large fields at high photopic luminances remains to be studied.

Bullough et al. (2011b) carried out a test of this model by using the same method as the second experiment of Rea et al. (2011) for HPS and MH light sources providing luminances equivalent to 2.7 or 21 lx. The results show that the model was able to accurately predict the brightness produced by the different light sources and illuminances. However, Fotios and Cheal (2011b) examined a wider range of light sources using side-by-side matching of two booths, the reference illuminance being 5 lx. This enabled the illumination ratio between two different light sources for equal brightness to be measured. Unfortunately, the predictions of the Rea et al. (2011) brightness model did not fit the measured illuminance ratios well. Of the alternative predictors examined, the ratio of the S/P ratios of the two light sources and the Sagawa (2006) brightness model gave good fits ($r^2 = 0.83$ and 0.89, respectively).

There is clearly still some work to be done in this area. The Rea et al. (2011) model is an attempt to produce a model of brightness that is consistent with the known physiology of vision but simple to apply. The ratio of S/P ratios is easy to apply but is purely empirical. The Sagawa (2006) brightness model does have a physiological basis but is not easy to apply. In addition, the CIE has recently entered the fray with a supplementary system of photometry based on Sagawa's model and designed to evaluate light sources in terms of comparative brightness. The system uses the concept of equivalent luminance to describe the brightness of a light or an object in photopic, mesopic and scotopic vision (CIE, 2011). How the appropriate balance between the ease of use, range of application and accuracy of prediction of these very different approaches will be resolved has yet to be determined, but there can be no doubt that light spectrum is important for the perception of brightness in mesopic conditions.

6.2.2.5 Sparkle

One other phenomenon of brightness that deserves mention is the perception of sparkle. Sparkle can be considered a positive form of glare, positive in that it stimulates people rather than causing them discomfort. The occurrence of sparkle is believed to be associated with the perception of a star pattern radiating from the source (Akashi, 2005). The variables that are known to be important are the size of the source, its luminance and the ambient luminance, all variables that are associated with glare. Akashi et al. (2006) attempted to identify the conditions required for sparkle to be seen by having observers look at a black surface pierced by an array of 32 circular apertures. Six different aperture sizes, six different aperture luminances and two background luminances were used, one background representing typical exterior lighting and one for interior lighting. Subjects were asked to classify the display as dull, glaring, bright or sparkling. Figure 6.6 shows iso-probability contours for the

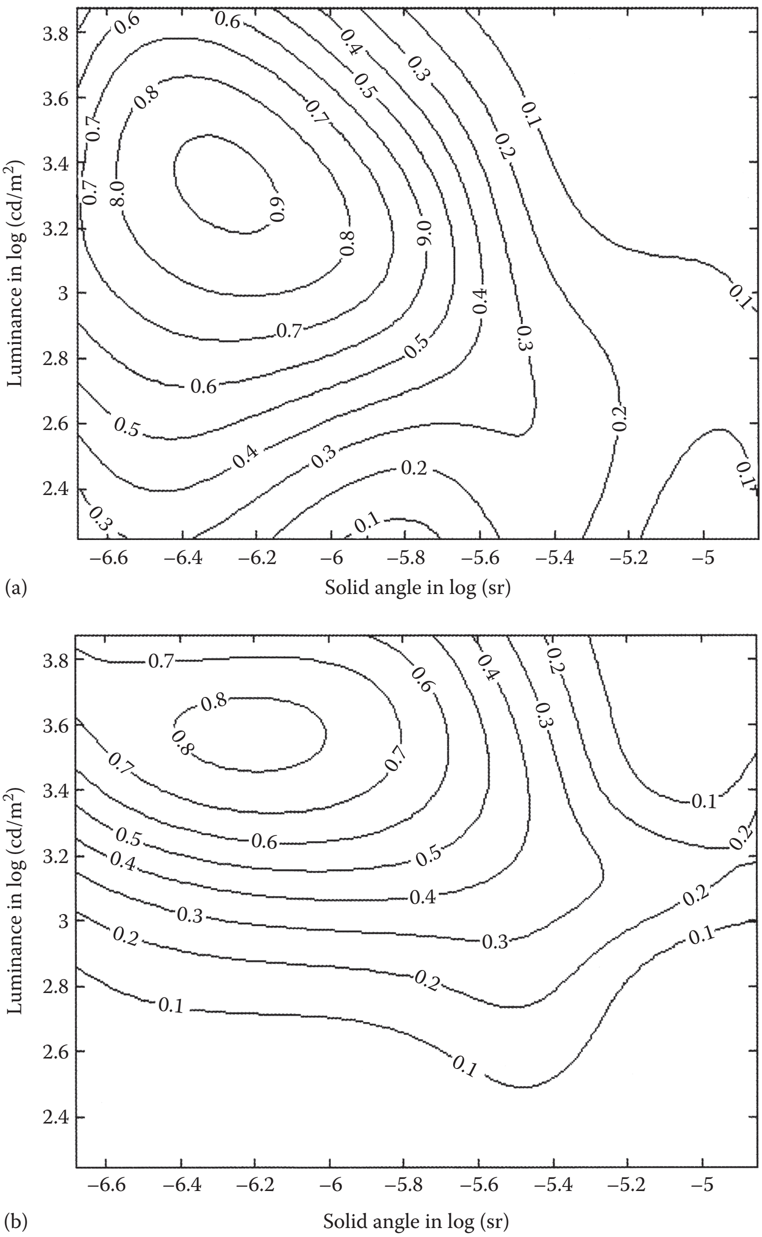


FIGURE 6.6 Iso-probability contours for perceiving sparkle. The contours are defined by the luminance and solid angle subtended at the observer on logarithmic scales for (a) low and (b) high ambient light levels. (From Akashi, Y. et al., *Lighting Res. Technol.*, 38, 325, 2006.)

perception of sparkle, the two dimensions being the solid angle subtended at the eye by an aperture and the luminance of the aperture. Examination of Figure 6.6 suggests that to have a high probability of seeing sparkle, the solid angle the source subtends at the eye should be about 0.5 μsr and a luminance of about 2000 cd/m^2 for exterior lighting and 4000 cd/m^2 for interior lighting. The data also showed that increasing the aperture luminance or the solid angle subtended further would increase the probability of describing the stimulus as glaring, while going to a lower aperture luminance would increase the probability of classifying the scene as dull.

6.2.3 Visual Clarity?

Another perception that is often claimed to be associated with light spectrum is that of clarity. The first paper in this field was that of Aston and Bellchambers (1969). They had people stand in front of two cabinets identically furnished with colourful objects and surfaces. The cabinets were lit by two different fluorescent lamps in identical luminaires so the light distribution was the same. The illuminance on the working plane of one cabinet was set to a fixed level, and the subject was asked to adjust the illuminance of the other '… so that the overall clarity of the scene is the same in both cabinets'. Further, overall clarity was defined as '… the satisfaction gained by you personally, discounting as far as possible any obvious differences in colour and brightness'. It was found that lamps with high CRIs were consistently set to a lower illuminance than lamps with low CRIs. In a later study, Bellchambers and Godby (1972) extended this research to full-size rooms and found very similar results, indicating that on average, a 24% higher illuminance was required for a lamp with moderate colour rendering properties (CRI = 55–65) to be seen as giving equal visual clarity to a lamp with very good colour rendering properties (CRI = 92), for a reference illuminance of 500 lx.

Over the years since the publication of this work, a number of researchers have followed the same path. One problem in comparing the resulting data has been that different studies have asked the observers to make the adjustment using apparently different criteria. Boyce (1977) asked observers to adjust the illuminances in two model rooms seen side by side for equal satisfaction with visual appearance. Fotios and Levermore (1997) asked the observers to match for visual equality. Despite the vagueness of these terms, there can be little doubt that the illuminance ratios set for each criterion do provide a measure of the relative effectiveness of different light spectra in providing some holistic impression, although whether that impression is based on the perception of brightness, clarity or something else is impossible to say. Until this quandary is resolved, any claims about light spectra influencing the perception of clarity should be treated with suspicion.

6.2.4 Colour Appearance

The most obvious factor determining the effect of lighting conditions on the colour appearance of a surface or a scene is the choice of light source. The choice of light source can have two effects on the colour appearance of a space. The first is to shift the overall colour appearance of the space. The second is to change the appearance of colours in the space relative to each other.

Regarding the overall colour appearance of the space, it is a matter of common observation that light sources with high CCTs give a space a cool colour appearance, while those with low CCTs produce a warm colour appearance. This difference will be most evident on entering the space. However, over time, chromatic adaptation occurs with the result that the difference in colour appearance is reduced. The magnitude of this reduction is evident in Boyce and Cuttle (1990) who showed that after more than 20 min, the perception of brightness and colourfulness in an achromatic room was the same for good colour rendering fluorescent lamps with CCTs ranging from 2700 to 6300 K. The effect on the relative colour appearance of different colours in the space is a much more important effect, regardless of the time available for chromatic adaptation. Light sources that have large gamut areas (see Section 1.6.4.2) and hence that increase the saturation of surface colours will increase the colourfulness of an interior.

There are other aspects than the choice of light source that matter for colour appearance. For example, there is the Bezold–Brucke effect. This effect is simply that changing luminance can change the hue of a colour. Increasing luminance makes reds yellower and violets bluer. Figure 6.7 shows the direction and magnitude of the Bezold–Brucke effect. The vertical axis shows the monochromatic wavelength of a field of luminance 7 cd/m^2 that matches the colour of the same-size field at 120 cd/m^2. The horizontal axis is the monochromatic wavelength of the higher luminance field (Boynton and Gordon, 1965). These luminances cover the range usually found in interior lighting.

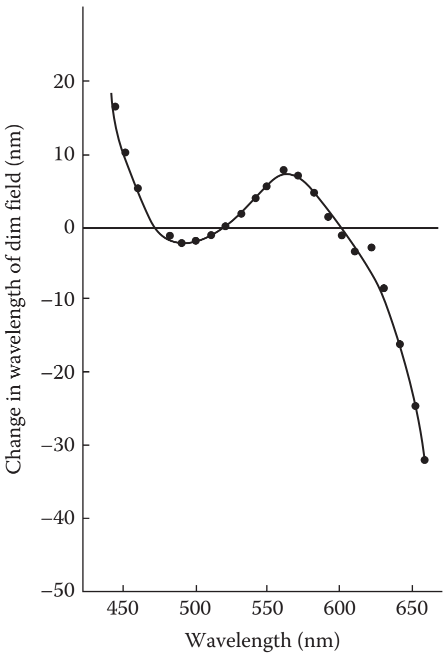


FIGURE 6.7 The Bezold–Brucke effect. The change in wavelength needed for one half of a bipartite field at 7 cd/m^2 to match the other half in hue at 120 cd/m^2. (After Boynton, R.M. and Gordon, J., *J. Opt. Soc. Am.*, 55, 78, 1965.)

One point of particular interest in Figure 6.7 is the fact that there are three wavelengths at which there is no shift in the hue, approximately 475, 507 and 570 nm.

Another factor that influences colour appearance is field size. The importance of field size is evident from the fact that CIE has found it necessary to introduce two standard observers for colorimetry. The CIE standard photopic observer is used for colour fields subtending less than 4° at the eye, and the CIE 10° standard photopic photometric observer is used for fields of colour subtending more than 4° (Wyszecki and Stiles, 1982). Figure 1.2 shows the spectral sensitivities of these observers. It is clear that increasing the field size from 2° to 10° makes the visual system more sensitive to the part of the visible spectrum below 550 nm.

There is another aspect of field size and colour appearance that will be evident to anyone looking at a large field, subtending say 10°, filled uniformly with light of a single colour. The appearance of the field will not be uniform. Rather, there will be a spot of diameter about 4°, with an ill-defined boundary, which differs in colour from the rest of the field. This spot is called the Maxwell spot and it will move around as the point of fixation moves. The existence of the Maxwell spot is mainly due to the existence of the macula, a yellow pigment that covers the fovea and the area immediately around it and acts a filter to the light reaching the retina.

These few examples should suffice to show that, like most other perceptions, the effect of lighting on colour appearance is not a simple matter and certainly not a simple matter when the possibility of an interaction between light source colour and the colours of the decor is considered (Mizokami et al., 2000). However, this complexity has not stopped attempts to provide a model of how the stimulus to the visual system affects the appearance of colours, seen separately or in combination with others. The most extensively developed of these has been produced by Hunt (1982, 1987, 1991). In 1982, Hunt proposed a set of cone spectral sensitivity functions that enabled predictions to be made of hue, lightness and chroma of colours seen under a medium photopic level of illumination. In 1987, the model was extended to provide predictions of brightness and colourfulness at any illuminance, no matter whether the visual system was operating in the photopic, mesopic or scotopic state. In 1991, the model was revised to make it easier to use and to cover situations in which a colour is seen among other colours as well as in isolation. The final model provides correlates of hue, lightness and chroma; brightness and colourfulness; saturation; relative yellowness–blueness; relative redness–greenness; and relative whiteness–blackness. The model has been shown to be consistent with physiological data in the form of changes in cone responses in monkeys as luminance is increased. It has also been shown to fit perceptions of brightness, hue, lightness and colourfulness, the effect of applying colour filters to part of a projected slide and the Bezold–Brucke effect for humans. The development of this and other models (Nayatani et al., 1994) led the CIE to produce a model of colour appearance suitable for colour management systems (CIE, 2004c).

This interest in the topic of colour appearance is a good thing because it may lead to the development of a metric or metrics of light source colour properties based on what it is that people care about, that is, how the light source will make colours appear, in isolation and in combination, over a wide range of luminances. It is also important because with the advent of light-emitting diodes (LEDs), there is the possibility of creating light sources with almost any required light spectrum. The spectra of LED light sources can be optimized using a genetic algorithm approach (Soltic and Chalmers, 2012), but the success of this approach will be limited by the fact that there are few colour metrics by which the optimization can be judged. This, together with the limitations of CRI (Guo and Houser, 2004), the one colour metric that is widely recognized, makes the need for more extensive and accurate metrics or models for colour appearance a matter of urgency.

6.3 HIGHER-ORDER PERCEPTIONS

6.3.1 Correlation Method

Most of the studies of the effect of luminous conditions on the simple perceptions of lightness, brightness and colour appearance have been undertaken using what has been called the correlation method. The correlation method is simple. It involves establishing a relationship between some subjective judgement of the lighting and a physical measure of the lighting, for example, between brightness and luminance. The subjective judgement can be made directly by using some form of rating scale or, indirectly, by adjusting a physical variable to match a subjective criterion, such as preferred illuminance. While the correlation method has been widely used, it has also been extensively criticized. These criticisms are related to the accuracy of the simulation, the plasticity of the response and the relevance and independence of the conclusions.

The criticism of accuracy of simulation arises from the fact that many of the experiments attempting to determine the effect of lighting conditions on perception have used abstract conditions, that is, uniform fields of luminance. This inevitably leaves some doubt about the validity of the relationships found for real interiors and particularly interiors that are complex and have a definite context.

The criticism of the plasticity of response arises from the observation that subjects tend to match the centre of a rating scale or the adjusted level to the centre of the range of conditions experienced (Poulton, 1977, 1989; Fotios and Houser, 2009; Logadottir et al., 2011), from the idiosyncratic responses produced when there is ambiguity in the instructions given to the observers (Rea, 1982) and from the variability in the response introduced when there is no link between the subjective judgement required and an obvious feature of the luminous environment (Tiller and Rea, 1992). The basic problem with the correlation method is that people are willing to make subjective judgements even when they make no sense. This places a heavy load on the experimenter when choosing a measurement method. Further, if responses are to be restricted only to those that have a link to an obvious feature of the luminous environment, then there is little prospect of ever understanding the impact of lighting on what might be called higher-order perceptions, such as complexity, formality and interest. Tiller and Rea (1992) suggest that one way out of this dilemma is to use semantic differential rating scales, not as an end in themselves but rather as a means of developing hypotheses about higher-order perceptions that could then be tested more stringently, perhaps using behaviour as a dependent variable. For example, if one lighting condition was shown to be considered more formal than another by using rating scales, it could be hypothesized that people would behave more formally in it. Such a hypothesis could easily be tested. Despite the ingenuity of this two-step approach, there have been few attempts to implement it.

The criticisms of relevance and independence remain, even when the measurement method has been carefully developed. The point is that obtaining a correlation between a physical measure and a subjective judgement is no guarantee that the psychological attribute represented by the judgement is relevant to people's everyday experience, and even if it is, when a number of such relationships are established, there is no reason to suppose that they represent independent dimensions.

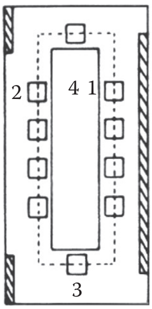
All these criticisms might suggest that there is little to be gained by applying the correlation method. This suggestion would be unfair. The correlation method has been used to identify lighting conditions that are considered uncomfortable by large numbers of people. Further, experience in the field suggests that the criteria developed to express this understanding are robust. What this implies is that the correlation method is useful for identifying visually uncomfortable lighting conditions. What the criticisms do suggest is that the correlation method is not suitable for exploring the impact of lighting on the higher-order perceptions. To explore higher-order perceptions, it is necessary to put people first, rather than lighting equipment, and to place them in a specific context, not in an abstract setting.

6.3.2 Multidimensional Methods

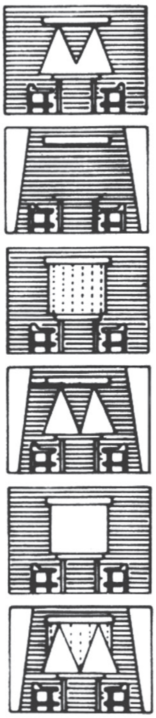
One seminal study in which a real interior was used was that of Flynn et al. (1973, 1979). In this study, 96 observers experienced a conference room lit in six different ways. The observers' responses were collected on 34 rating scales. The instruction to the observers was to evaluate the room. Factor analysis was then applied to the data. Factor analysis is a statistical technique by which an enormous quantity of data can be ordered so that the minimum number of underlying independent dimensions on which the observers are basing their responses can be revealed. Factor analysis also gives a measure of the extent to which each individual rating scale is related to the independent dimensions. Figure 6.8 shows the six lighting installations used by Flynn et al. to light the conference room, the room being furnished with the same conference table and chairs for all six lighting installations. Figure 6.9 shows the five independent dimensions on which the impressions of the room under the six lighting installations are based. Also given are the individual rating scales that were most strongly related to each dimension. Based on the rating scales that are most strongly related to each dimension, the five dimensions were identified as evaluative, perceptual clarity, spatial complexity, spaciousness and formality. The numbers located along each scale indicate the mean rating on that scale for each lighting installation. A simple examination of Figure 6.9 shows that only three of these dimensions have much separation between the lighting conditions, these being the evaluative, perceptual clarity, and spaciousness dimensions.

A closer examination of the different rating scales in Figure 6.9 reveals the richness of the information available. For example, the pleasant–unpleasant scale, which is the scale most strongly related to the evaluative dimension, shows that the installations that are most pleasant (installations 4 and 6) have a common feature, as do the

Plan



Sections



Sections	Luminance (cd/m2) see plan for position on				Illuminance (lx)
	1 Table	2 Wall	3 Wall	4 Ceiling	Table
1 Overhead downlighting low intensity	1.2	0.3	0.0	1.7	110
2 Peripheral wall-lighting, all walls	7.9	19.9	32.5	8.9	110
3 Overhead diffuse, low intensity	2.9	3.7	2.6	80.5	110
4 Combination: overhead downlighting (1) + end walls	1.4	1.0	26.3	1.7	110
5 Overhead diffuse, high intensity	21.9	119.9	26.7	1404.7	1100
6 Combination: overhead downlighting (1) + peripheral (2) + overhead diffuse (3)	11.6	33.5	38.3	82.2	320

FIGURE 6.8 A plan of the conference room, six schematic illustrations of the six lighting installations used and some photometric measurements of the lighting conditions used. (After Flynn, J.E. et al., *J. Illum. Eng. Soc.*, 3, 87, 1973.)

two installations that are most unpleasant (installations 3 and 5). Installations 4 and 6 provide lighting on the working surface, that is, the table, and on the room surfaces. Installations 3 and 5 provide diffuse lighting on the table only. This supports the view that for good-quality lighting, it is necessary to light both the task and the room, something that has long been argued by practitioners of lighting design.

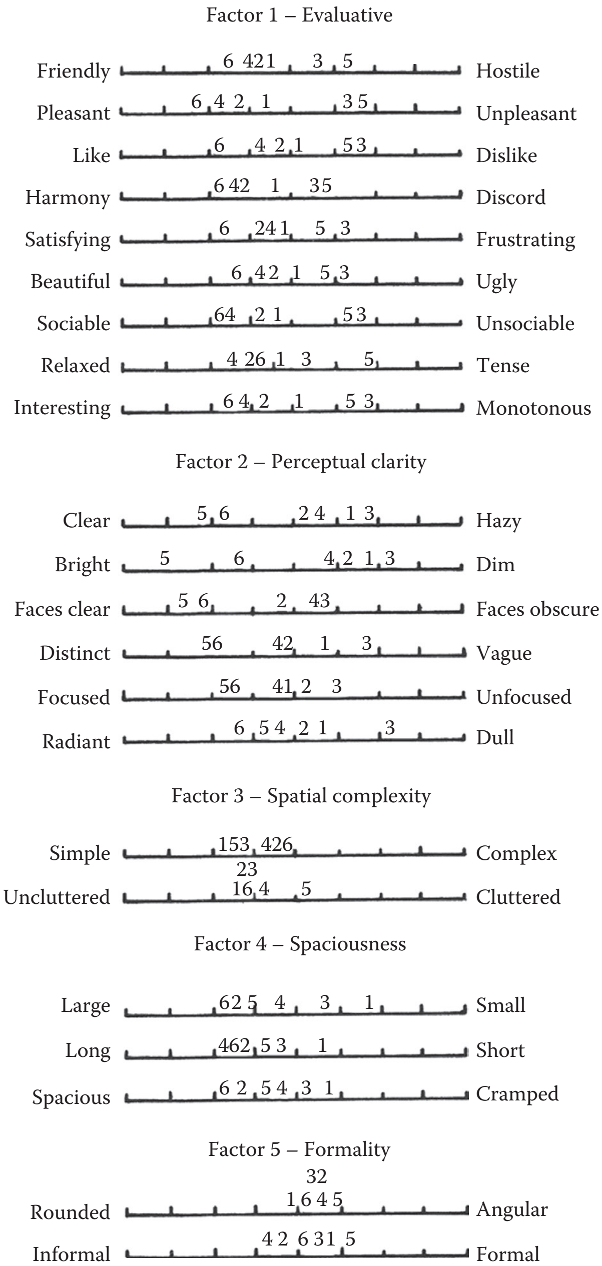


FIGURE 6.9 The five factors identified from the rating of the conference room lit by the six lighting installations shown in Figure 6.8. The rating scales most strongly related to each factor are shown under each factor title. The mean rating for each installation on each scale is given by the appropriate installation number, that is, installation 6 has the mean rating closest to the pleasant end of the pleasant–unpleasant scale. (After Flynn, J.E. et al., *J. Illum. Eng. Soc.*, 3, 87, 1973.)

The second dimension, perceptual clarity, is apparently related to the illuminance on the table. As might be expected, the higher illuminance installations are considered to give greater perceptual clarity. Further, the separation on the clear–hazy rating scale, which is the one most strongly linked to the dimension of perceptual clarity, is much less between 320 lx (installation 6) and 1100 lx (installation 5) than between 110 lx (installations 1–4) and 320 lx (installation 6). This is just what would be expected from what is known about the non-linear response of visual performance to illuminance (see Section 4.3.5) and about peoples' preference for illuminance in an office setting, measured using the correlation method (see Section 7.2).

The third dimension, spaciousness, is more difficult to understand. The separation between the different lighting installations is smaller and the number of scales related to the dimension is fewer, although the placing of the different lighting installations is consistent across scales. What makes it difficult to understand is that the lighting installations that provide a perception of greater spaciousness have several different features. The installations that provide light on the table alone, particularly at a low illuminance, make the room appear to be small and cramped. The installations that light the walls alone or both the walls and the table give an impression of a large and spacious room.

Such information can be used to answer questions of interest to the designer. For example, suppose the designer has a choice of either lighting the conference table to a high illuminance or having a lower illuminance on the table but some light on the walls. From the data discussed previously, it is apparent that the former approach will give the impression of a room that is clear but rather unpleasant, while the latter will be assessed as less clear but more pleasant and spacious. Such conclusions do not tell the designer what to do, but they do supply some information on which to base a decision.

It can be concluded that the rating scale/factor analysis approach produces much useful information. It also overcomes some of the criticisms of the correlation procedure. It ensures that the dimensions identified are independent and, by using rating scales related to the impression of the room rather than just the lighting, ensures that the results reflect the importance of the lighting variables to the particular context. For example, for the range of conditions used in the conference room, it is clear that changing the lighting has a much bigger effect in the perceptions of perceptual clarity than on the perception of spaciousness.

However, there is still one big limitation of this approach. It still rests on the use of a finite number of rating scales selected by the experimenter. If there are no scales about a particular aspect of the visual environment, then there is no way a dimension related to that aspect can be found. Flynn et al. also examined another multidimensional approach that eliminates the need to select rating scales by eliminating their use. Specifically, all they asked the observers to do was to rate how different two installations were from each other, for all possible pairs of installations. Flynn et al. used this method to examine the same lighting installations in the same conference room used for the rating scale/factor analysis study, but with a different set of 46 observers. By applying a multidimensional scaling (MDS) analysis, the number of independent dimensions that are needed to describe the differences between the installations can be identified. These n dimensions are then used to form an

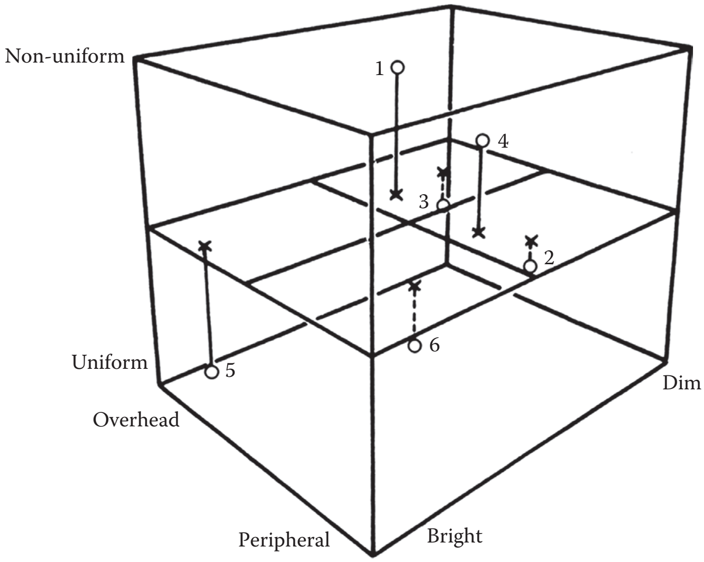


FIGURE 6.10 The positions of the six lighting installations in the conference room shown in Figure 6.8 in the 3D space derived from the MDS analysis. (After Flynn, J.E. et al., *J. Illum. Eng. Soc.*, 3, 87, 1973.)

n-dimensional space in which the individual installations can be located. Flynn et al. found that for the six installations in the conference room, a 3D space was the minimum necessary to explain the data. Figure 6.10 shows the three dimensions and the locations of the individual installations. From the positions of the installations relative to each axis, the three dimensions were named peripheral/overhead, uniform/non-uniform and bright/dim. As the dimensions are identified from the installation characteristics, there is no possibility of directly evaluating the meaning of the dimensions. The best that can be done is to tell which installations are considered more or less different from each other and the independent dimensions on which they differ. This may seem a rather meagre return for such a large investment, but it is only when the rating scale/factor analysis and the difference/MDS approaches are combined that their full value becomes apparent. From the rating scale/factor analysis approach, the three dimensions that most clearly separate the installations are evaluative, perceived clarity and spaciousness. Choosing a rating scale strongly related to each of these dimensions allows stepwise multiple regression equations to be calculated for the mean ratings on each scale and on the three MDS dimensions. The evaluative dimension gave a correlation of 0.83 on the overhead/peripheral MDS dimension the perceptual clarity dimension gave a 0.99 correlation on the bright/dim MDS dimension and the spaciousness dimensions gave a correlation of 0.69 with the uniform/non-uniform MDS dimension. These correlations demonstrate that there is good but not perfect agreement between the dimensions obtained by the two approaches and the location of the various installations on those dimensions. This agreement allows the MDS dimension which the observers use to distinguish between the installations to be related to the observers' rated impressions of the conference room. For example, it is clear that the extent to which the room is considered pleasant is mainly related to the existence of peripheral lighting, although as the introduction of the uniform/non-uniform MDS dimension increases the correlation with rated pleasantness to 0.92, having a non-uniform distribution of light, is also of value. This conclusion could have been reached from examination of the factor analysis alone, but this result was obtained by asking the observer specific questions. It is good to have the conclusions confirmed by a procedure that allows the observer to use whatever he or she wishes to use to make judgements.

It can be concluded that both the rating scale/factor analysis and the difference/MDS analysis procedures provide rich information about the perceptions of lit spaces, particularly if used together. However, before adopting these procedures and applying them wholesale, it would be as well to consider the stability of the dimensions identified and the position of different installation types on them. Flynn et al. (1975) examined this question in two stages. First, they applied the rating scale/factor analysis method to five different lighting installations in three different sized rooms, but all with the same context, that is, conference rooms. The same factor structure was obtained for all three rooms and the locations of individual lighting installations on the dimensions were similar. They also examined the dimensions found for different lighting installations for rooms with a different context. In this study, they used an auditorium. Based on the ratings obtained, it was clear that there was some consistency in the impression given by different lighting installation types. High illuminances were related to greater clarity, peripheral lighting and low illuminances produced a pleasant impression and the use of high illuminances and peripheral lighting produced an impression of spaciousness. Such results suggest stability of impression and support Flynn's concept that lighting provides a number of cues that people use to interpret a space and that these cues are at least partly independent of the room that is being experienced (Flynn, 1977). But all these results come from one source. Before accepting such an important conclusion, it would be as well to examine what others have found.

An obvious comparison is with the results of Hawkes et al. (1979). The subject of the evaluation was a small rectangular office lit in 18 different ways (Table 6.1). The illuminance on the desks was always 500 lx, but the distribution in the rest of the office varied greatly. Factor analysis of the data collected, omitting the evaluative scales, revealed two independent dimensions. One was the brightness dimension, so called because it had such rating scales as bright/dim, strong/weak and clear/hazy associated with it, although it also had the cramped/spaciousness scale related to it. The other dimension was simply named interest because the rating scales strongly related to this dimension were simple/complex, mysterious/obvious, uninteresting/interesting and commonplace/special. The positions of the different installations on the plane formed by these two dimensions are shown in Figure 6.11. From this figure, it can be seen that the brightness dimension is clearly related to the amount of light in the room, while the interest dimension appears to be primarily related to light distribution. Also shown in Figure 6.11 are iso-preference contours indicating those areas on the plane that are preferred to different extents. The top right-hand corner contains the installations that are most preferred. Such installations are both bright and interesting. It is important to appreciate that these two dimensions are independent.

TABLE 6.1
Lighting Installations Used by Hawkes et al. (1979)

1	Regular array of ceiling-recessed fluorescent luminaires with opal diffusers
2	Incandescent downlights in a regular array plus fluorescent wall washing of the two end walls
3	Regular array of ceiling-recessed fluorescent luminaires with prismatic panels
4	Fluorescent wall washing of the two side walls
5	Fluorescent desk lights at either side of each desk
6	Incandescent spotlights at the end of the room and on the desks
7	Incandescent downlights in a regular array
8	Incandescent spotlighting of the side walls plus fluorescent wall washing of the right-hand wall
9	Regular array of ceiling-recessed fluorescent luminaires with prismatic panels
10	Fluorescent desk lights at either side of each desk plus fluorescent wall washing of the left-hand wall
11	Regular array of incandescent downlights plus incandescent spotlighting of the two side walls
12	Regular array of ceiling-recessed fluorescent luminaires with specular louvres plus fluorescent wall washing of the right-hand wall
13	Fluorescent wall washing of the right-hand wall
14	Regular array of ceiling-recessed fluorescent luminaires with specular louvres plus incandescent spotlighting of the two side walls
15	Incandescent spotlighting of all walls and desks
16	Regular array of ceiling-recessed fluorescent luminaires with specular louvres
17	Fluorescent wall washing of all four walls
18	Fluorescent desk lights at either side of each desk plus incandescent spotlighting of the two side walls

Making an uninteresting situation interesting does not make it brighter. Making a dim situation brighter does not make it more interesting. The value of the data shown in Figure 6.11 is that the most preferred installations have certain common features, as do the least preferred installations. All the most preferred installations contain some element of variety in lighting produced by spotlighting or wall lighting. All the least preferred installations consist only of regular arrays of recessed fluorescent lighting providing uniform lighting. While this is useful for design purposes, there is one caveat that should be noted. All the installations provided a similar illuminance on the desks, that is, on the work area. It is doubtful if the installations producing variety of lighting would have been preferred if the variety had led to a much lower illuminance on the work surface. What this caveat implies is that the results in Figure 6.11 apply to the lighting of the space, given that the lighting of the task is adequate.

One criticism of the studies of Flynn et al. and Hawkes et al. is that the number of subjects was too small for a robust factor analysis, given the number of scales used. Veitch and Newsham (1998a) overcame this problem by having 292 observers rate the appearance of a multi-person office furnished with cubicles and lit by one of nine different lighting installations. The evaluation was made with the participant sitting in a cubicle in the office after having worked on a computer and on paper for about 5 h. Factor analysis of the ratings revealed three dimensions named brightness, visual attraction and complexity, although in total they only explained 46% of the variance, probably because the differences between the lighting installations were smaller than in the earlier studies. Examination of how the different lighting

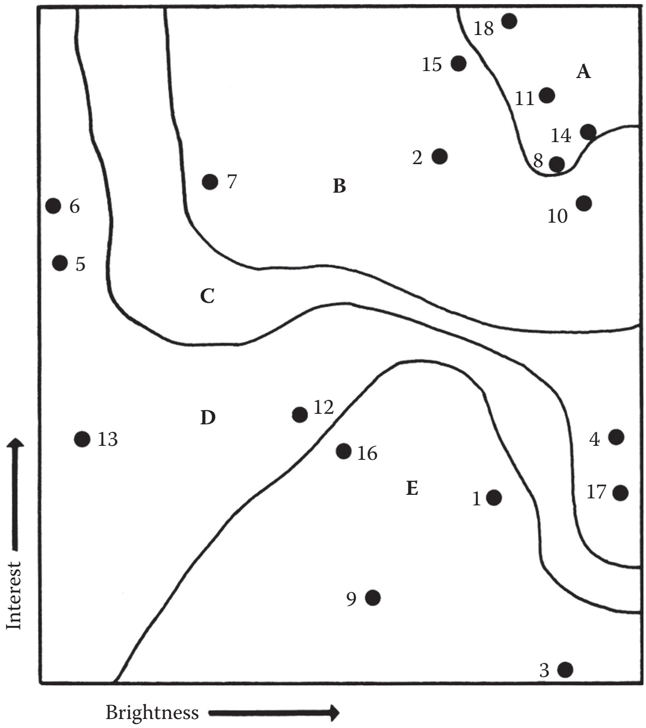


FIGURE 6.11 A map showing the location of the types of office lighting listed in Table 6.1 on two dimensions, interest and brightness, identified by factor analysis. Superimposed on this map are iso-preference contours based on preference ratings of the same lighting installations. These contours define areas for equal preference from area A (most preferred) to area E (least preferred). (After Hawkes, R.J. et al., *J. Illum. Eng. Soc.*, 8, 111, 1979.)

installations related to each of these dimensions showed that the direct lighting system produced a greater impression of brightness than indirect lighting, that lighting installations using parabolic luminaires were considered less complex and less bright than installations using lensed luminaires and that task-ambient lighting installations were considered less bright than direct lighting installations.

The interesting point about these three sets of studies, separated by almost 30 years and all using functional interiors where work is to be done, is the similarities and differences in their factor structures. All show that brightness is one dimension on which people evaluate a visual environment. Another appears to be something to do with variety, meaning non-uniformity in light distribution away from the work surface. After that, there is no agreement. Flynn et al. (1973) have a dimension of spaciousness. Veitch and Newsham (1998a) have a dimension of complexity and Hawkes et al. (1979) do not have a third dimension. The fact that brightness is a consistent dimension on which the visual environment is evaluated should not be too surprising, given that brightness is related to the amount of light in the space and how well we can see is determined by the amount of light available. The importance of brightness is also consistent with an information-processing model of environmental appraisal (Kaplan, 1987). This model rests on the idea that the information available in a scene is central to our appraisal of it and brightness is a marker for how much information is revealed. As for variety, there is no doubt that humans need some variety, but not too much. Monotonous environmental conditions, if taken to extremes, lead to cognitive breakdown (Corso, 1967). On the other hand, too much variation in environmental conditions is disliked (Nasar, 2000) and, if taken to extremes, can lead to confusion and distress.

Another thing to say about variety is that, unlike brightness, variety can be introduced through aspects of the visual environment other than lighting. For example, variety can be introduced into a room by changing the decor, by changing the furnishings and by changing the people in it. One application in which variety in visual stimuli is purposefully created using décor, furnishings, layout, signage, as well as lighting is retailing where brand identity is important. Custers et al. (2010) conducted a field experiment in which the perceived atmosphere in 57 Dutch clothing stores assessed by one group was related to the characteristics of the shop lighting and the type of interior design as assessed by two other groups. The perceived atmosphere of the shops was expressed on four dimensions: cosiness, tenseness, liveliness and detachment. Lighting was found to have some influence on three of these dimensions. Brightness was negatively related to cosiness and positively to tenseness. This means that greater brightness in a shop makes it seem less cosy and more tense. Glare and sparkle were related to liveliness, so more glare and sparkle made the atmosphere more lively. Unfortunately for those who believe in the overwhelming importance of lighting, the strength of these influences was modest. As for the interior design, the orderliness of the shop was found to be strongly positively related to the perception of detachment and negatively related to the perception of liveliness. Clearly, lighting matters to the perception of a space, but in the real world, there are many other aspects of the visual environment that are also important. Using a non-uniform light distribution is but one way of introducing variety and may not be the most potent.

What all these suggest is that any attempt to try and link specific lighting conditions to higher-level perceptions and to apply them across many different contexts is doomed to fail. There are too many other factors beyond the photometric conditions that influence higher-order perceptions, and these factors will vary with different contexts for different cultures. It may still be possible to make a link between lighting conditions and higher-order perceptions for specific contexts in specific cultures, but how valuable such a finding would depend on how specific the conclusion was. There is little merit in determining what type of lighting makes a meeting room look formal if that perception changes dramatically when the furniture is changed.

6.4 PERCEPTION OF OBJECTS

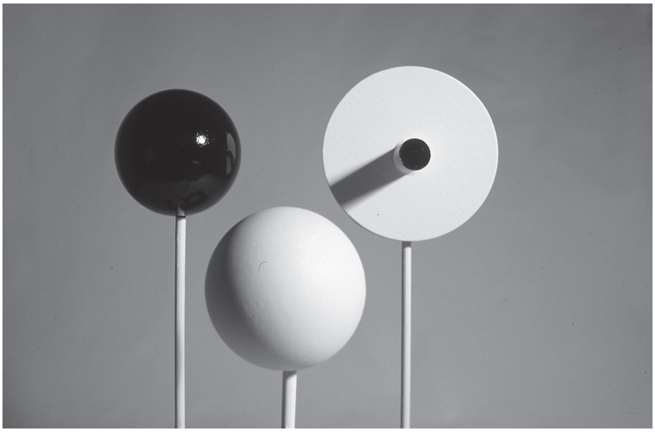
This rather dismal conclusion about the impact of lighting on higher-order perceptions in spaces should not be taken to mean that lighting cannot make a dramatic difference to how an object in such a space is perceived. Rather, it should be taken to mean that the perception will depend on the nature of the object as well as the lighting. This is evident in the work of Mangum (1998). He examined the perception of three museum objects under six different lighting installations, all subject to the conservation constraint that no illuminance on the object could exceed 50 lx. The perception of the object was identified by the use of a balanced (positive and negative) word list from which observers had to select all the words that applied to their perception of the object. When viewing a doll, clothed in materials varying in texture, colour and reflection properties, under diffuse illumination, the words most frequently chosen to describe the observers' perceptions were unattractive, unpleasant, obscured, veiled, bland, boring, mundane and ordinary. When the same doll was lit with directional lighting, the words most frequently used were interesting, attractive, eye-catching, clear, pleasant, revealing, dramatic and spectacular. Similar results were found for a plain vase, although other forms of directional lighting were required to produce more dramatic perceptions for this object.

Clearly, altering the lighting can change the higher-order perceptions of an object, but how can the relevant features of the lighting be described? Assuming there is enough illumination on the object for the detail to be seen clearly, which is not always the case in museums because the objects there may be likely to deteriorate when exposed to too much optical radiation, there are two aspects of the lighting that matter, the light spectrum and the light distribution.

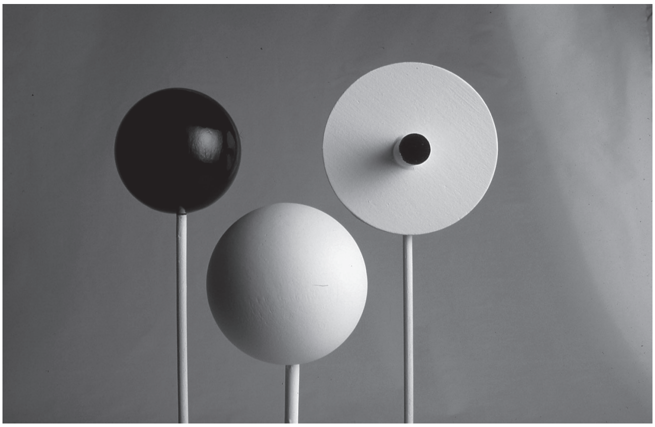
The spectrum of the light that illuminates the object interacts with the spectral reflection properties of the object to produce the stimulus delivered to the visual system. This stimulus influences how the colours will be perceived. There are two general metrics for assessing the merit of a spectrum for revealing the colours of an object. The first is gamut area. The larger is the gamut area, the more saturated hues will become. This is useful information but ignores the possibility that the hues may be more saturated than is natural. It also ignores the possibility that the hue may be distorted to some degree. The second metric is the CIE general CRI. This measures how well a colour will be seen relative to how it might appear under a reference light source with the same CCT. Where colours need to be seen correctly, as in an art gallery, a CRI of 90+ is recommended.

Both the gamut area and the CRI of a light source are general metrics in that they are based on a small number of sample colours and reduce the complexities of colour perception to a single number. They are of use where a number of diverse objects are to be seen under the same lighting system, although some of the alternatives discussed in Section 1.6.4 might be better. However, for a complete understanding of how a specific object will appear when illuminated by a specific light source, it is necessary to go to the CIE colour appearance model (CIE, 2004c). Given all the necessary inputs, this model is capable of predicting the brightness, lightness, hue, chroma and saturation of a surface colour and hence how an object will appear when illuminated by a specific light source.

As for the light distribution, one approach is to classify the effects of directional lighting on objects into three patterns: the shadow pattern, the highlight pattern and the shading pattern. Figure 6.12 shows three objects specifically designed to reveal these patterns (Cuttle, 2008). The flat vertical disc with a peg sticking out is designed to reveal the shadow pattern, the peg acting as a shadow caster. The black gloss sphere is designed to reveal the highlight pattern. The matte white sphere is designed to reveal the shading pattern. In completely uniformly diffuse lighting,



(a)



(b)

FIGURE 6.12 Three devices used to show the sharpness and flow of light produced by (a) a narrow beam spotlight and (b) a large window. The disc with the protruding peg shows the shadow pattern. The gloss black sphere shows the highlight pattern. The matte white sphere shows the shading pattern. (From Cuttle, C., *Lighting by Design*, Architectural Press, Oxford, U.K., 2008.)

such as occurs in an integrating sphere, there will be no shadow pattern, no highlight pattern and no shading pattern. Figure 6.12 shows what happens when a single small point light source, such as a narrow beam spotlight, and a single large area diffuse light source, such as a window, are used to illuminate an otherwise unlit space. When the spotlight is used, a single strong shadow is evident, the highlight is sharply defined and there is a clear shading pattern. When the window is used, the shadow and highlight patterns are both softened but the shading pattern is little changed. The characteristics of the lighting that are associated with these patterns are called sharpness and flow. The patterns evident when the spotlight is used show that such lighting has both sharpness and flow but when the window is used, the lighting has only flow. In an integrating sphere, the lighting has neither sharpness nor flow.

The difference in the shadow and highlight patterns when the spotlight or the window is used suggests that, for the same light output, it is the size of the source of light that is important (Worthey, 1990). The potential a light source or luminaire has to deliver sharpness and hence strong shadows and highlights can be quantified by the highlight ratio (Cuttle, 2008). This is given by the following equation:

$$H = \frac{0.04}{\sin^2\left(\cos^{-1}\left(1 - (\Omega/2\pi)\right)\right)}$$

where

H is the highlight ratio

Ω is the solid angle subtended by the luminaire at the point of measurement (μsr)

This equation implies that it is light sources that subtend the smallest solid angle at the measurement point that have the greatest potential to produce a perception of sharpness. It is important to note the word potential, for two reasons. First, lighting alone cannot generate highlight and shadow patterns. For a highlight pattern to occur, objects with a significant level of specular reflection have to be present. For a shadow pattern to occur, some form of shadow caster has to be present. Second, the highlight ratio is a function of the light source, but the lighting in a space may be provided by many light sources. If these increase the surface luminances in the space, the perception of sharpness will be reduced. The use of solid angle in the equation is also important because it implies that even physically large sources of light have the potential to produce sharpness at a point if they are far enough away. Table 6.2 gives some highlight ratios for a range of light sources and luminaires at a distance of 2 m. These values explain why candles and light sources where a hot filament is directly visible enhance the appearance of classical glass chandeliers, while compact fluorescents (CFLs) do not.

As for the perception of flow of light, this concept was introduced by Lynes et al. (1966). At the time, this was revolutionary. This paper pointed out that

TABLE 6.2
Highlight Ratios for a Range of Different Light Sources and Luminaires for a Viewing Distance of 2 m

Light Source	Highlight Ratio
60 W clear incandescent	25,000
Candle flame	6,700
60 W pearl incandescent	1,600
MR11 halogen spotlight	500
2 arm CFL	110
600 mm × 600 mm fluorescent diffuser	1.4

Source: After Worthey, J.A., *J. Illum. Eng. Soc.*, 19, 142, 1990.

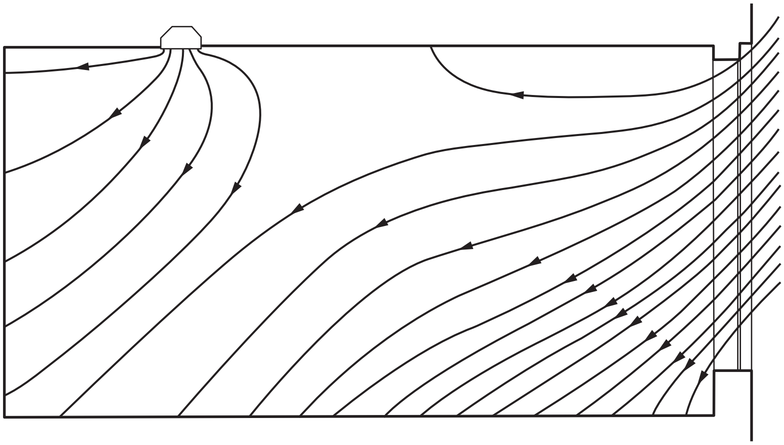


FIGURE 6.13 The flow of light across a vertical plane in a room lit by a side window and electric lighting mounted on the ceiling. The flow of light is indicated by the direction of the illumination vector measured at a grid of points in the plane. (After Lynes, J.A. et al., *Trans. Illum. Eng. Soc.* (*Lond.*), 31, 65, 1966.)

although every child learns that light travels in straight lines, the perception of light crossing a room lit by a side window and ceiling-mounted electric lighting is of a curve. The flow of light can be partially quantified by measuring the illumination vector at a series of points across a space. Like all vectors, the illumination vector has two components: a magnitude and a direction. In principle, both can be found by measuring the difference between the illuminances falling on the opposite sides of a flat disc and identifying the orientation of the disc where this difference is a maximum. Then, the magnitude of the illumination vector at the measurement point is the maximum difference between illuminances on the two sides of the disc, and the direction is the normal to the surface of the disc receiving the higher of the two illuminances. By making such measurements in the space, it is possible to construct a diagram similar to that used to show a magnetic field but, in this case, showing the flow of light (Figure 6.13). Unfortunately, this is not the whole story as far as the magnitude is concerned. A magnitude based on an illuminance difference ignores the absolute illuminance values, so the same difference might represent a very large or very small variation of illuminance. To overcome this problem, the scalar illuminance is measured. The scalar illuminance is the average illuminance falling on the surface of a small sphere placed at the measurement point. The magnitude of the flow of light is then given by the ratio of the magnitude of the illumination vector to the scalar illuminance, the vector/scalar ratio.

The vector/scalar ratio is a useful measure of the potential a lighting installation has for producing a strong flow of light. Vector/scalar ratio can vary from 0 to a maximum value of 4, a value of 0 occurring in an integrating sphere, while a value approaching 4 occurs when a collimated beam of light is shone across a totally black room. Table 6.3 shows the strength of the flow of light associated with different values of vector/scalar ratio.

TABLE 6.3
Effect of Different Vector/Scalar Ratios on the Strength of the Flow of Light and the Consequences for Object Appearance

Vector/Scalar Ratio	Strength of the Flow	Appearance
3.5	Dramatic	Theatrical
3.0	Very strong	Strong contrasts, detail in shadows not discernable
2.5	Strong	Suitable for display, too harsh for faces
2.0	Moderately strong	Pleasant for distant faces
1.5	Moderately weak	Pleasant for near faces
1.0	Weak	Soft lighting for subdued effects
0.5	Very weak	Flat, shadow-free lighting

Source: After Cuttle, C., *Lighting by Design*, Architectural Press, Oxford, U.K., 2008.

Vector/scalar ratio is an interesting metric, representing as it does the effect of light distribution in three dimensions. One object of widespread interest for which it has been studied is the human face. Cuttle et al. (1967) have shown that for the human face, the preferred vector/scalar ratio lies in the range 1.2–1.8 and the preferred vector illumination direction is for an altitude of 15°–45° from the horizontal rather than from overhead (90°). Despite its ingenuity and its possible value for design, as a lighting metric, vector/scalar ratio seems to have fallen on stony ground, being little used in research or design (Gongxia and Yun, 1990; Cuttle and Brandston, 1995). Partly, this is because of the perceived difficulty of measurement. However, it can be calculated from measurements of illuminance falling on the six faces of a cube (Cuttle, 1997, 2008), something that should certainly make it easy to estimate with modern software packages. It is to be hoped that now that technology has caught up with the concept, vector/scalar ratio will be more widely used to assess proposed lighting designs.

By changing the light spectrum and the shadow, highlight and shading patterns in a space, the perception of objects in the space can be changed, for good or ill. How an object is perceived will depend on the nature of the object and to what extent the form, texture, colour and reflection properties of the object are modified by the change in lighting. This is where the skill of the lighting designer becomes apparent. Of course, objects can vary enormously in their form, texture, colour and reflection properties. This is not often the case for functional interiors. For most functional interiors, the surfaces are diffusely reflecting, with limited variations of texture, colour and form, and the distribution of light is much more limited than in lighting intended for retail, hospitality or entertainment purposes. What this means is that the higher-order perceptions in functional interiors are most likely to be influenced by the lighting when the architect has provided a space that has an interesting form, containing surfaces that vary in texture and colour, and the lighting designer has used his or her skills to complement and enhance the architecture, thereby producing something of visual interest.

6.5 SUMMARY

The link between the stimuli provided to the visual system by a luminous environment and the perception of that environment is often weak. This is because the perception of the luminous environment depends on the state of adaptation of the visual system, the background against which objects in the environment are seen and the observers' past experience and knowledge. Nonetheless, the luminous environment is the starting point of perception and lighting can be used to change the luminous environment. Therefore, lighting can change the perception of spaces and the objects in them.

How stable lighting's influence on the perception of a space will be will depend on how closely the perception is linked to the operation of the visual system and how much opportunity there is for non-lighting factors and for past experience and knowledge to intervene. Simple perceptions, such as lightness, brightness and colour appearance, show robust links to the luminous environment. Higher-order perceptions, such as formality, spaciousness and complexity, show more tenuous links.

The simple perception of lightness is linked to the reflectance of a surface, but given a very wide range of luminance, even the perception of lightness will change. Specifically, as the luminance decreases, the lightness of a surface decreases. The simple perception of the brightness of a small uniform field is linked to luminance by a power law, but in real rooms, it is also influenced by the light distribution in the room, the luminance of the luminaire and the spectrum of the light. Results in this area show that increasing the luminance of the room surfaces will increase the perception of brightness, as will choosing a light source capable of providing more stimulation to short-wavelength cones. As for luminaire luminance, depending on the luminance and area of any bright patches on the luminaire, the brightness of the room can be enhanced or diminished. Balancing the luminance and area so that the bright patch on the luminaire is perceived as sparkling will also enhance the brightness of the room. Increasing the luminance further so that the luminaire becomes glaring will diminish the brightness of the room.

The simple perception of colour appearance is linked to the spectrum of the light source and the luminance. How strong an effect the choice of light source has depends on whether the space is essentially achromatic or one containing many coloured surfaces. The effect of light source will be much greater for the latter conditions than the former because chromatic adaptation can offset some of the difference due to different light spectra in an achromatic room but cannot offset the effect of the light spectrum on the saturation of colours in the room.

The effect of the luminous environment on higher-order perceptions is much less certain. This is because higher-order perceptions, such as formality, are influenced by the whole of the environment, not just the luminous environment, as well as the context of the space and the culture of the observer. The only consistent evidence suggests that the lighting in almost all functional spaces is evaluated on the dimensions of brightness and visual interest, the former being related to the amount of light in the space and the latter being enhanced by a non-uniform distribution of light away from the work area.

This should not be taken to mean that lighting always has such limited effects on the perception of non-functional spaces and objects. There is clear evidence that by changing the lighting, the perception of objects can be changed from drab and boring to eye-catching and dramatic. Everyday experience suggests that the same is true of non-functional spaces, such as restaurants, shops and theatres. The problem with functional spaces is that the possible lighting effects and the materials they have to work with are often limited by the need to provide good visibility for work over a large portion of the space. In such spaces, lighting is most likely to have an effect on higher-order perceptions when the architect has generated an attractive space and the lighting designer has produced lighting that provides sufficient brightness in the task area and enhances the architecture to provide some visual interest elsewhere.

Section III

Specifics

7 Lighting for Offices

7.1 INTRODUCTION

Over the last 50 years, the office has become the place where more and more people spend their working lives. The technology available to agriculture and industry in developed countries is such that large numbers of people are no longer required to produce food or manufactures, and if they are, then globalization of business means that production is moved to where wages are lower. In 2012, in the United States, the largest economy in the world, 62% of people employed worked at least part of the time in offices.

Further, over the last 30 years, the nature of office work has changed dramatically, not because the purpose of office work has changed but rather because the means to do the work have changed. The purpose of office work remains the collection, recording and distribution of information, together with the making of decisions based on that information and the direction of effort to carry out the decisions made. What has changed over the last 30 years has been the immense growth in the ability to collect, record and distribute information rapidly, over vast distances, electronically. This process began with the introduction of the personal computer, gained strength with the development of communication through e-mail, continued with immediate access to information via the World Wide Web and is still developing with the growth in the capabilities of mobile devices.

There can be little doubt that the consequences of these changes will be of great interest to the social historian, but what do they have to do with lighting? The answer is a great deal. In the paper-based office, the primary surface to be viewed is horizontal, and increasing the amount of light in the office makes any information on that surface more visible. In the computer-based office, the primary surface to be viewed is inclined, and increasing the amount of light in the office makes the information displayed on the self-luminous screen less visible. Therefore, the widespread introduction of computer-based technology made a fundamental change in the requirements for lighting an office. As long as office work was undertaken on paper, lighting the surface of the desk was what mattered. With the introduction of computer-based technology, it appeared that a completely different approach to office lighting would be needed because an entirely screen-based office was technically possible and the visibility of the displays produced by early screen technology was very sensitive to the lighting conditions. A walk around any office today will reveal very few that are completely screen-based as well as showing that modern screen technology is much less sensitive to lighting conditions and much more variable in location. This means that any lighting installation designed for an office today has to be satisfactory for materials that are self-luminous, that is, computer screens, and seen by reflected light, that is, paper, and for lines of sight that can vary widely.

This chapter is devoted to the lighting of offices and is organized around the choices the lighting designer has to make, namely, the illuminance to be provided, the light source to be used, the type of luminaire and its layout and the nature of any lighting controls. This chapter is only concerned with the features of a display that make it more visible and/or more comfortable to use in as far as they interact with the lighting of the office. Anyone who is interested in the features of the display that affect visibility and comfort independent of the lighting is referred to Roufs (1991).

7.2 ILLUMINANCE

For many years, the most widely used criterion of good lighting in an office has been the average illuminance on a horizontal plane at desk height, a surface conventionally called the working plane. Until recently, many national and international lighting recommendations focused attention on the illuminances to be provided on this plane (SLL, 1994; IESNA, 2000a; BSI, 2002). This was a reasonable approach when most office work involved the use of paper placed on desks and there was uncertainty as to where in the offices these desks would be. It was reasonable because the desk was where detail needed to be seen and provided the reflectances of the room surfaces were not low, the luminaires emitted some light upwards and there was a window providing some daylight, the appearance of the office would be acceptable (Jay, 1968). However, the arrival of early computer technology with low-luminance screens meant that the luminous intensity distribution of luminaires and daylight coming through windows had to be tightly controlled to avoid reflected images being seen in the screens. Too often, the outcome of this approach was an office with a lot of light on the horizontal working plane but little on the walls and ceiling thereby producing a cave-like appearance that was considered unsatisfactory. Today, screen technology has developed to such a degree that the visibility of the detail displayed on screens is rarely adversely affected by the lighting of the room. This, together with the recognition that there are many different locations from which information is required in modern offices, has led to the latest recommendations being made for illuminances on the work plane, wherever it is, on walls and ceilings and on vertical planes within the office (BSI, 2011a; IESNA, 2011a; SLL, 2012a).

The history of illuminance recommendations in different countries shows considerable variation (Mills and Borg, 1999), but the trend for virtually all countries is for an increase in recommended illuminances for office work from the 1930s until the early 1970s, followed by either a stabilization or a decline. This trend reveals that the illuminance recommendations are not simply a matter of logical deduction. Rather, making illuminance recommendations is a human activity that is influenced by both practical and political considerations, in addition to the state of knowledge of how illuminance affects task performance and visual comfort (Boyce, 1996). The practical considerations are matters of technology. For example, it can plausibly be argued that one of the driving forces that led to the general increase in recommended illuminances from the 1930s to the 1970s was the introduction and development of the fluorescent lamp and the high-intensity discharge (HID) lamps, light sources with dramatically higher luminous efficacies than the incandescent lamp they replaced. The political considerations are financial and consequential. The financial consideration is the cost of providing a given illuminance relative to the benefits obtained. Increases in this cost tend to lead to declines in recommended illuminances. The consequential considerations refer to such impacts of burning fuel to generate electricity for lighting as increased global warming and increased dependence on foreign fuel suppliers. These financial and consequential considerations can lead to sudden changes in lighting practice as the perceived costs of lighting weigh much more heavily than the benefits in the mind of the user.

The observation that illuminance recommendations, and presumably therefore the illuminances installed, have varied over time makes it interesting to consider if there is any stability in the illuminances preferred for offices. Veitch and Newsham (2000) examined this question using a windowless office filled with six cubicle workstations and equipped with four different lighting installations, all of which could be switched and dimmed. Two people, matched for age and sex, occupied two workstations at the same time, but only one had control of the lighting systems. At the start of the day, this person was asked to choose the lighting system he/she liked and could adjust that lighting to what he/she preferred. After that, the lighting was unchanged throughout the day. During the day, both people performed paper- and computer-based office tasks. At the end of the day, the person who had not had the opportunity to adjust the lighting was given a chance to set the lighting to his/her preference. Figure 7.1 shows the distribution of the illuminances on the desktop chosen by all 94 people who made these choices. The mean desktop illuminance is 423 lx with a standard deviation of 152 lx.

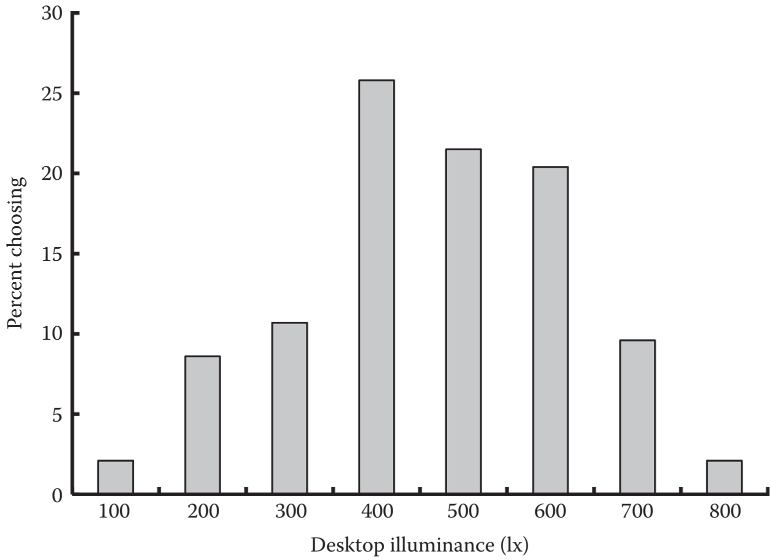


FIGURE 7.1 Percentage of people choosing different desktop illuminances in a windowless office, half made at the beginning of the day and half at the end of the day. The frequencies are collected in bins with a width of 100 lx. (After Veitch, J.A. and Newsham, G.R., *Lighting Res. Technol.*, 32, 199, 2000.)

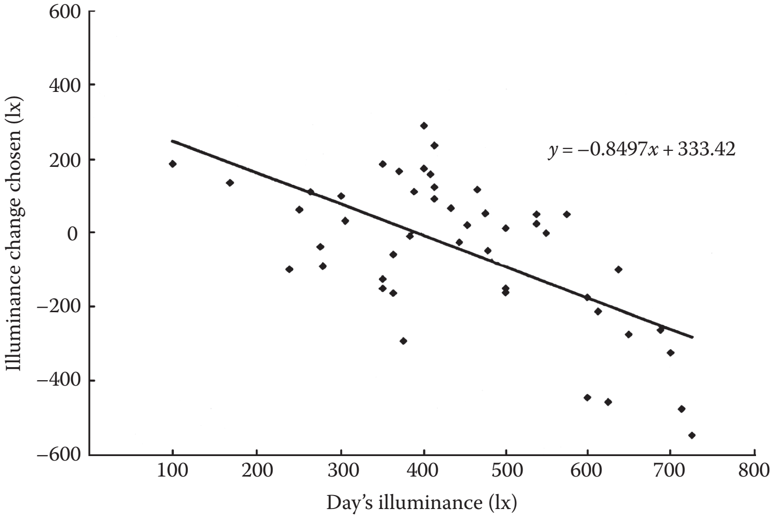


FIGURE 7.2 The illuminance change chosen at the end of a day's work plotted against the illuminance on the desk experienced during the day. (After Newsham, G. and Veitch, J., *Lighting Res. Technol.*, 33, 97, 2001.)

Newsham and Veitch (2001) used the same data to explore the difference between those who choose the illuminances at the start of the day and at the end. Figure 7.2 shows the linear regression of the change in illuminance on the desk made at the end of the day by 47 subjects, plotted against the illuminance they had experienced throughout the day. The regression line crosses $y = 0$ at 392 lx, that is, this is the illuminance experienced during the day after which no change was desired. For higher illuminances, the change at the end of the day is to reduce the illuminance, and for lower illuminances, the change is to increase the illuminance. Many of the participants reported that they had adjusted the lighting to reduce the luminance of reflected images of the overhead luminaires on the computer screen. When Newsham and Veitch (2001) eliminated these illuminance changes, the null illuminance increased to 458 lx. Both these illuminances are close to the values recommended for offices in many countries that lie in the range 300–500 lx.

A common feature of Figures 7.1 and 7.2 is the wide variation in individual preference for illuminance. These individual differences matter because Newsham and Veitch (2001) also found that the deviation between the subjects' illuminance preferences and the illuminance they experienced during the day was a statistically significant predictor of the subject's mood and satisfaction with the lighting. Similar large individual differences in preferred illuminances for office work have been found in a simulated office with limited daylight after people who could adjust the lighting of their cubicle by dimming the luminaire overhead had spent a day doing a variety of office tasks (Boyce et al., 2006a). For this data, the mean desktop illuminance chosen was 458 lx with a standard deviation of 201 lx, the minimum and maximum desktop illuminances selected being 242 and 1176 lx, respectively.

It is interesting to consider why, if the illuminance is an important factor in determining the achievable level of visual performance, there should be such large individual differences in preferred illuminances. The answer is that the size and contrast of most office tasks are high enough to ensure that visual performance is effectively saturated (Cuttle, 2010; Rea, 2012). It is a fact that the day of the fifth carbon copy is over. Photocopiers and laser printers have seen to that. This means that the illuminance on the workstation can be changed over a wide range without affecting visual performance, which implies that the basis of preference for illuminance in offices is something else. One possibility is that people are judging whether or not they think there is enough light in the office to see whatever it is they expect to be asked to do there. What this comes down to is brightness. As discussed earlier, one dimension on which people consistently evaluate a lighting installation is brightness (see Section 6.3.2). The illuminance provided is related to the perception of amount of light in the space and hence to brightness. Another possibility is simply that when there is no obvious effect on visibility or comfort, people prefer what they are used to, which, for the last generation of office workers, has been an illuminance of about 500 lx. Yet another is that different people have different preferences for the contrast between the work area and the surrounding areas, some liking a very uniform illuminance pattern while others prefer a much more varied pattern. Regardless of which, if any, of these possibilities is correct, there can be no doubt that different people have very different preferences for the illuminance to be provided on the workplace in offices.

Despite this variability, illuminance on the workplace remains a primary design criterion. This is because it is easy to predict and to measure and it can be clearly linked to the costs of the lighting installation. Attempts have been made to get the people responsible for many lighting installations to consider factors other than illuminance by providing simple guidance (IESNA, 2000a, 2011a; SLL, 2005) but with little apparent effect. Further, one obvious way to ensure that office workers

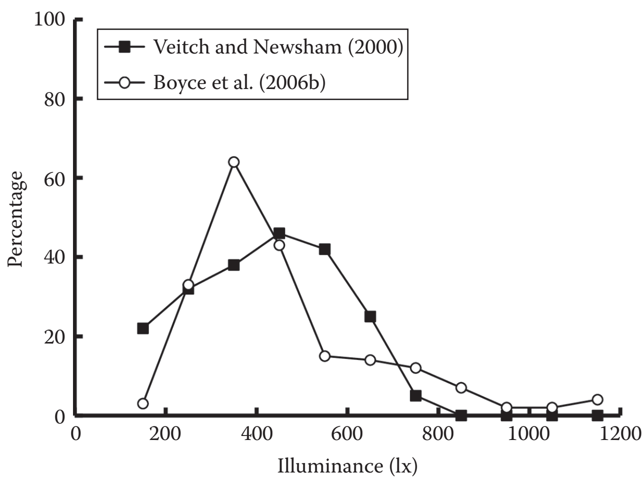


FIGURE 7.3 The percentage of people whose preferred illuminance was within 100 lx of a fixed illuminance plotted against different fixed illuminances. (After Boyce, P.R. et al., *Lighting Res. Technol.*, 38, 358, 2006a.)

have the illuminance they like, by giving them individual dimming control, is rarely practised. This means that the predominant method of lighting an office delivers a one-size-fits-all illuminance. Given this situation, it is appropriate to consider what that illuminance should be. Figure 7.3 shows the percentages of participants in two office lighting studies who, at a given fixed illuminance, are within 100 lx of their preferred illuminance. In one study (Veitch and Newsham, 2000), the illuminance at which the maximum number of people was within 100 lx of their preferred level was around 450 lx, while in the other (Boyce et al., 2006b), it was around 350 lx. This suggests that an illuminance of 400 lx is most likely to satisfy the majority of people in an office today, although as Figure 7.3 shows, it will only be a small majority.

7.3 LIGHT SOURCES FOR OFFICE LIGHTING

By choosing the light source, the lighting designer determines the spectrum of the light used to illuminate the office and hence influences the appearance of the office and the people in it. The first major decision to be made on light source is the balance between daylighting and electric lighting. The second major decision is the type of electric light source to be used.

7.3.1 Daylight

Daylight always deserves consideration. It deserves consideration because people desire it. The fact that daylight is desired can be shown by evidence from four sources. From research comes the fact that almost any study which asks office workers about which light source they would like to illuminate their work area reveals a strong preference for daylight (Markus, 1967; Cuttle, 1983; Veitch and Newsham, 2000; Al Marwaee and Carter, 2006). From behaviour comes the observation that those of higher status in an organization are commonly given offices closer to windows or with more windows. From advertising comes the frequent claim that one electric light source or another is like daylight, the rationale being that a light source like daylight is what people desire. Finally, from finance comes the fact that the rent charged for daylit office spaces is more than for non-daylit office spaces. There is little doubt that daylight is desired by people in offices and in other spaces. But why is daylight so desirable? The usual responses to this question range from surprise that it should be asked at all, through comments about daylight being natural to quasi-religious statements about the sun. Such answers are not helpful. Rather, it is necessary to consider daylight from the points of view of physics, physiology and psychology.

Physically, daylight is simply electromagnetic radiation in the wavelength range that is emitted by the sun, scattered in the atmosphere and absorbed by the photoreceptors of the human visual system. The actual wavelengths present in daylight will vary over the day, with meteorological conditions, with latitude and with season. It is this variability in spectral content and the fact that, at all times, it is a continuous spectrum with power in all parts of the visible wavelength range that separates daylight from the electric light sources commonly used in offices. Nonetheless, there are electric light sources available, such as the xenon lamp, the sulphur lamp and some filtered incandescent lamps, that have a spectral content similar to that which occurs with daylight on some occasions. Thus, there is no unique physical characteristic of daylight that separates it from all other light sources.

Physiologically, the response of the human visual system to the light spectrum is determined by the spectral sensitivities of the three cone photoreceptors and the rod photoreceptor. All these photoreceptors have a broad spectral response (see Figures 2.6 and 2.7). This implies that the visual system should be capable of functioning equally well using light consisting of many different wavelength combinations. This belief is supported by measurements of visual acuity, contrast sensitivity and other threshold visual functions made under different light sources (Boff and Lincoln, 1988). The only threshold performance that is strongly influenced by the spectral content of the illuminant is colour discrimination, which is not unexpected given that changes in the spectral content of the illuminant will change the stimulus presented to the visual system. Likewise, measurements of suprathreshold visual task performance have shown little difference between light sources, provided the different light sources produce the same illuminance and the tasks do not require colour discrimination or resolution of fine detail (Smith and Rea, 1979).

The conclusion to be drawn from these observations is that there is no physical or physiological reason for daylight to be so desirable. This leaves some psychological factor as a possible source of the desire for daylight. For daylight to be attractive psychologically, it has to fulfil some basic human needs. One such is the ability to see well. Daylight is characterized by the high illuminance it is capable of providing and the excellence of its spectrum for colour discrimination and colour rendering. These two properties give daylight the potential to produce good vision. Whether it does or not depends on how the daylight is delivered. Daylight delivered through windows can produce a bright interior in which people look their best and can see details and colours well. Equally, daylight delivered through windows can produce discomfort glare and very high-luminance reflections on display screens, both of which hinder vision.

Another human need is for variety. The results discussed in Section 6.3.2 show that peoples' preferences for the lighting are based on two independent dimensions, brightness and interest. The brightness dimension is related to the amount of light perceived in the space, while the interest dimension is related to the variation of light patterns in the space. The most preferred office lighting is that which provides both brightness and interest. Daylight can be used to provide lighting that is both bright and interesting, in the sense that it can provide a lot of light and that light has a distribution which shows meaningful variation over space and over time.

Given that variety is what is being sought, it is important to note that the usual means by which daylight is provided, namely, a window, provides variety through a view-out in addition to variety in the lighting of a space. This raises the question of whether the commonly expressed preference for daylight is really a preference for a window with a view-out. I believe this question poses an artificial dichotomy. It seems much more likely that both aspects are important. Certainly, when asked about important aspects of windows, both the provision of daylight and the provision of a view-out are frequently mentioned. Further, it is necessary to recognize that a view-out can sometimes have a psychological cost, in terms of loss of privacy.

Heerwagen (1990) argues that what people seek from windows is visual access without visual exposure. To meet this aim, a careful balance between view-out and view-in is required.

Given that daylight appears to be strongly desired by most people, it is reasonable to ask what happens when people are asked to work without daylight, when it is available outside. These conditions, which occur in windowless rooms, have produced a consistent pattern of response. For example, in an extensive field survey, Al Marwaee and Carter (2006) found that 65% of people working in spaces with windows were satisfied with their visual environment but only 45% of those working in windowless spaces were satisfied, despite the presence of daylight delivered through tubular guidance systems. Further, when the windowless space is small and the occupant has little possibility to leave the space, the lack of variety is noticeable and the lack of windows is disliked (Ruys, 1970). However, in large spaces, such as school classrooms (Larson, 1973) and factories (Pritchard, 1964), the lack of windows has a much more variable impact. This may be because in a large space, where there are many other activities going on and there is a lot of interaction between people, there is often plenty of stimulation in the environment. In a small office, it may be that the view-out of the window is the only source of environmental stimulation. Some support for this idea comes from the work of Heerwagen and Orians (1986). They observed that people occupying small private offices without windows used twice the number of visual materials to decorate their offices as did people whose offices had windows, and that those materials were dominated by views of nature. Overall, the work on peoples' reactions to windowless buildings supports the idea that a view-out is valued, but it does not necessarily support the primacy of view-out over the provision of daylight. In windowless offices, surrogate daylight is provided by the electric lighting; it is a surrogate view that is missing.

A supplementary question to that concerning windowless buildings is if daylight is desired so strongly, how willing are people to give it up when it is available? Observation of almost any multi-storey office building will reveal that people are willing to give up daylight when it also causes visual and thermal discomfort. Measurements of the use of window blinds in multi-storey office buildings have shown two trends. The first is that window blinds are increasingly likely to be pulled down as the sun begins to shine on the window and so cause solar glare and radiant heating. This might be expected. Less expected is the second trend that many of these blinds are kept down even after the sun has ceased to shine directly on the window and that, in some cases, the blinds are left in the down position for days, months or years (Rea, 1984). This latter trend suggests that the desire for daylight is limited when it is known to cause discomfort at some time.

The observation that blinds are commonly used to limit daylight when the sun is shining on the window raises the question, is the response to sunlight different from that to skylight? Wang and Boubekri (2011) conducted an experiment in which people were asked to sit in different positions in a room lit by a large window. Some seating positions were exposed to direct sunlight, while others were not. While seated, the people did a visually easy cognitive task requiring the use of short-term memory. There was a decline in positive mood after doing the cognitive task, but people close to the sun patch and having a better view-out declined less than those whose positions were far from sunlight and the window. Interestingly, people who sat in the sun patch and closest to the window showed a greater decline. What this implies is that while sunlight is considered to be desirable, this is only likely to be the case when it does not cause visual or thermal discomfort. Both sunlight and skylight can cause visual and thermal discomfort, but sunlight is more likely to do so.

Yet another supplementary question is, if daylight, *per se*, is strongly desired, might it be expected that when there is plenty of daylight available in a space, people will switch off or dim the electric lighting to minimize its impact on the daylighting? Moore et al. (2003) conducted a long-term study of office lighting controlled by the occupants and found that the electric lighting was switched on at the start of the day and then left on throughout the day, regardless of the amount of daylight available. Begeman et al. (1994, 1995) made prolonged measurements in a set of deep, private offices with large windows where the electric lighting could be dimmed. They found that, given the opportunity, people tended to increase the amount of electric light as the amount of daylight in the office increases. This behaviour is consistent with a desire to balance the luminance of the window and the surfaces near it with the luminances of the surfaces deep in the room. It also implies that the overall pattern of light distribution in the room is more important than the purity of daylight. This lack of concern with the absolute purity of daylight is again evident in the widespread use of tinted glazing in buildings and the wearing of tinted sunglasses by people.

So why is daylight desired? The observations above suggest that the reason why daylight is so popular as a means of lighting is that, if carefully designed, daylighting delivered through windows provides a comprehensive package which can meet the requirements of good lighting by revealing both the task and the space clearly and the requirement for environmental stimulation by variation of lighting conditions in the space and a view-out through the window. By comparison, electric lighting installations, if well designed, can provide good visibility of the task but often do little for the space and rarely provide any variation over time or space. Even when electric lighting installations are designed to produce some variation over time and space, the variation is usually simple, repetitive and apparently arbitrary compared to the complexity of daylight variation and the meanings that such variations carry. But the desire for daylight is not unlimited. When daylight through windows is inappropriate, either because it causes visual or thermal discomfort or because of excessive environmental stimulation, or because of loss of privacy, it is common to reduce daylight and eliminate the view-out by covering the windows in some way.

What all these suggest is that the desirability of daylight is not so much a matter of its inherent superiority but of the limitations of electric lighting systems. This conclusion is consistent with the results reported by Cuttle (1983). From a series of questionnaire surveys of office workers in England and New Zealand, he concluded that the preference for daylight could be attributed to the belief that working by daylight results in less stress and discomfort than working by electric light. The belief was not so much that daylight was beneficial but rather that working by electric lighting was deleterious to health, particularly in the long term. Of course, this may have been due to the specific forms of electric lighting used in the offices surveyed, which may have been visually uncomfortable, but it is interesting to realize that similar beliefs about the negative effects of fluorescent lamps on people were found in a survey of

2950 members of the public attending a New York State Fair in 1991 (Beckstead and Boyce, 1992). A bias against some widely used forms of electric lighting can be expected to produce a desire for daylight, some form of lighting being essential and daylight being the most obvious alternative.

Given that daylight is desired, could the provision of daylight in a workplace, as opposed to electric light, have a positive effect of task performance? Existing knowledge offers little support for the idea that the provision of daylight, *per se*, can guarantee an improvement in productivity (Cuttle, 1983; Norris and Tillett, 1997). However, there is a conceptual framework that can be used to identify if and how the provision of daylight might enhance productivity (see Section 4.2). Lighting conditions can have an impact on task performance through three routes. The first is by changing the stimulus the task presents to the visual system or by changing the operating state of the visual system. How changes in the amount of light, the spectral content of light and the distribution of light alter either the stimuli a specific task presents to the visual system or the operating state of the visual system is well understood. Further, the effects of these changes on the performance of the visual component of a task can often be predicted through a model of visual performance (Rea and Ouellette, 1991). For this route, daylight is just another form of lighting, which, in a given situation, will produce a specific amount of light with a known spectral content and, depending on how it is delivered, with a known light distribution. Therefore, depending on the form of daylight, visual performance can be enhanced or degraded.

The second route is through mood and motivation. It has been established that when people are in a good mood, they tend to be more positive about the work, more cooperative and more creative, attributes which are considered desirable in many working situations (Isen and Baron, 1991). The role of mood is also evident in the model of the relationship between satisfaction with environmental features and job satisfaction constructed from data collected in an extensive field survey of 15 open-plan offices in Canada and the United States (Veitch et al., 2007). All the offices were furnished with individual cubicles as is usual in these countries. Statistical analysis of the detailed physical and subjective measurements produced a three-factor model, the three factors being satisfaction with lighting, satisfaction with privacy/acoustics and satisfaction with ventilation/temperature. These three factors influenced overall environmental satisfaction, which in turn had a direct impact on job satisfaction. This is important because job satisfaction has been shown to impact job performance (Judge et al., 2001). Further, business units with higher average job satisfaction have a lower turnover of staff and improved profitability (Harter et al., 2002).

This model implies that providing daylight through windows can make a contribution to job satisfaction, but it is important to appreciate that it is not sufficient to guarantee job satisfaction. There are too many other factors that influence job satisfaction, such as the nature of the work, relationships among staff and remuneration, for that to be possible. This may explain the variability that occurs in the attempts that have been made to measure the effects of daylight availability on task performance. Hedge (1994) measured the performance of a clerical task on a computer in a room lit by different electric lighting systems, with and without windows.

He found a small but statistically significant improvement in task performance when windows were present. Whether this occurred because the presence of windows improved the stimuli the tasks presented to the visual system or changed the operating state of the visual system or because the subjects were in a better mood or if all three occurred is not clear. Stone and Irvine (1991) also measured the performance of a managerial task in a room that had a window or was windowless. In this case, no statistically significant effects of having a window were found for task performance or mood. It is clear that the provision of daylight through windows is not a sure recipe for an improvement in performance at an individual or at an organizational level.

Daylight also has photobiological effects (see Chapter 3). Reduced exposure to daylight for a long time is known to be associated with a form of clinical depression, called seasonally affective disorder (SAD) (see Section 14.4.2) and may lead to vitamin D deficiency (see Section 14.5.2). SAD usually occurs in the winter but not in the summer and increases in prevalence at higher latitudes (Terman, 1989). The symptoms associated with SAD are feelings of sadness and irritability, as well as lethargy, oversleeping and overeating. These symptoms tend to lead to difficulties at work and in personal relationships. These symptoms have been successfully treated by exposure to electric light either as a massive daily light dose (Terman et al., 1989) or as a simulation of the sun rising at dawn (Avery et al., 1994). The former might be expected; it is simply providing the missing dose of light. The latter is not expected, but it has been suggested that exposure to daylight in the early morning may be a very effective way of reducing the concentration of the hormone melatonin, which is associated with sleep, and hence kick-starting the working day. How effective daylight is compared with a cup of strong coffee remains to be determined. Clearly, we have some way to go before we fully understand this impact of light exposure on people. However, there is no doubt that the symptoms of SAD are real, are associated with reduced exposure to light and are disruptive to everyday life. There is also the possibility that many more people suffer from subclinical SAD in which the symptoms of SAD are present but in a mild form (Kasper et al., 1989a). If this is so, then the impact of lack of daylight on productivity may be underestimated, particularly where daylight exposure before and after work is limited for several months of the year.

This analysis of why daylight is desired and how it might affect productivity carries a number of implications, both conceptual and practical. In conceptual terms, one implication is that to understand the impact of daylight on peoples' feelings and behaviour, it is necessary to stop treating daylight as an end in itself and to consider its provision as a means to an end. This suggests paying attention to the more profound psychological aspects of life, such as the desire for knowledge, social isolation, privacy and stimulation, rather than the physical characteristics of the form of daylight provision.

In practical terms, the implications are that the designers of daylight delivery systems need to control solar glare and radiant heating from sunlight, provide a view-out, perhaps limit the view-in and pay attention to the lighting of the space as well as the lighting of the task. Designers of electric lighting systems need to remember to work with daylight as much as possible and recognize that both the lighting of the task and the lighting of the space matter.

7.3.2 Electric Light Sources

The great disadvantage of daylight as a light source is that it fails every day, for a long period. Therefore, every office is designed with an electric lighting system that is used after dark and, frequently, throughout the day as well. Currently, the most commonly used electric light source in offices is the fluorescent lamp, although the light-emitting diode (LED) may soon surpass it. Other electric light sources, such as the incandescent lamp or the MH discharge lamp, could be used but rarely are. The reason why the incandescent lamp is rarely used is that it has a much lower luminous efficacy and a much shorter life than the fluorescent lamp, both factors that increase the costs-in-use of a lighting installation (see Section 1.7.4). The MH lamp is rarely used because the low ceiling heights typical of offices, usually less than 3 m, impose limits on the maximum possible luminance of luminaires, restrictions that are difficult to meet with an MH lamp without using a low wattage version that has a low luminous efficacy or using a higher wattage version in an inefficient luminaire.

Fortunately for the lighting designer, fluorescent lamps come in many different sizes and shapes and with many different light spectra. It is this last attribute that is most obvious to the office worker. The effect of light spectrum on office work has to be considered on four levels. The first is the effect on the performance of chromatic tasks. The second is the effect on the performance of achromatic tasks. The third is the effect on alertness and mood. The fourth is the preference for different light spectra.

7.3.2.1 Light Spectra and Chromatic Tasks

There are three main roles for colour in office tasks. The first is to increase the visibility of the task by providing a colour difference between the task and its immediate background, in addition to any luminance contrast, for example, printing in different colours. The second is to increase the conspicuity of the task by marking it with a different colour from others around it thereby enhancing the speed of visual search, for example, highlighting changes in a text. The third occurs where the colour itself is meaningful, for example, the colour of a warning sign or a filing label. For the first and second roles, the exact colour used is immaterial. The only things that matter are, for visibility, how different it is from the colour of the immediate background, and, for visual search, how different it is from all the other colours in the area to be searched. For the third role, the accurate naming of the colour is important. The choice of light source can influence the effectiveness of coloured stimuli for all these roles because light spectrum is one of the factors that determine colour appearance.

Regarding visibility, O'Donell et al. (2011) have shown that the colour difference between a task and its immediate background can play a role in the level of relative visual performance that can be achieved. Specifically, when the luminance contrast is low, a high level of relative visual performance can only be achieved if there is a strong colour difference between the task and its immediate background. When the immediate background is white, the level of colour difference can be predicted from the excitation purity of the colour of the task. Figure 7.4 shows the excitation purities for different colours required to achieve a relative visual performance equal to or greater than 97% at different luminance contrasts. Examination of Figure 7.4 reveals two important facts. The first is that the colour difference is only important

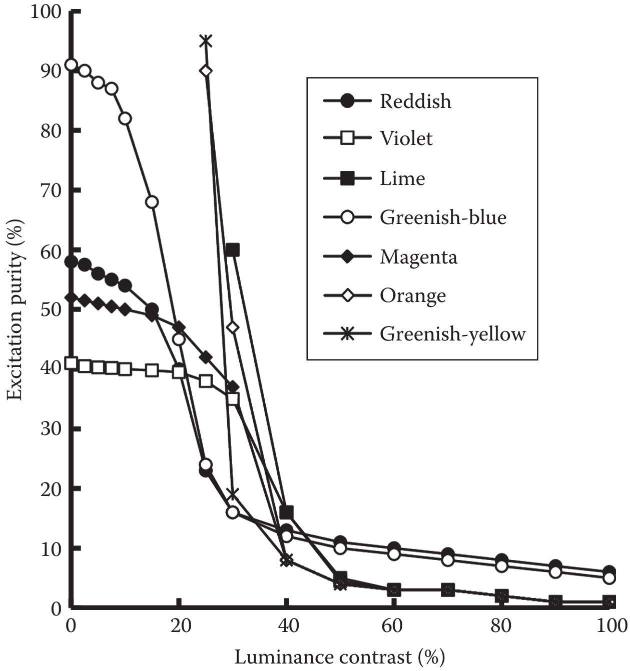


FIGURE 7.4 The excitation purity for different colours required to achieve a relative visual performance of 97% or greater at different levels of luminance contrast. The adaptation luminance was 40 cd/m^2. The target was circular and subtended 83 μsr at the eye. (After O'Donell, B.M. et al., *Lighting Res. Technol.*, 43, 423, 2011.)

for relative visual performance when luminance contrast is below about 0.40. The second is that different colours require different levels of excitation purity to achieve the same level of relative visual performance. A relative visual performance of 97% or greater can be achieved at zero luminance contrast by the violet, magenta, reddish and greenish-blue colours with excitation purities in the range 42%–90% but not by the lime, orange and greenish-yellow colours when the luminance contrast is less than 0.20, no matter how high the excitation purity. The choice of light source has an effect on the excitation purity that can be achieved with a given colour, a capability that should be closely related to the gamut area index of the light source.

Regarding visual search, Williams (1966) studied the search times for finding a specified item from a display of 100 items that could vary in size, shape, colour and the information they contained. In fact, the information within each item was a two-digit number. The observer was asked to locate a particular number, the number being specified either alone or together with various combinations of the size, colour, and shape of the item it was in. For example, the inspector could be asked, *Find the number 45 which is in a large blue square* or simply *Find the number 45*. The mean search times for the different target specifications are given in Table 7.1.

From Table 7.1, it can be seen that the longest mean search times occurred when the number alone was specified and the shortest mean search times occurred when the colour and size of the item in which the number was located were also specified.

TABLE 7.1
Mean Time to Find a Target for Different Target Specifications

Target Specification	Mean Time (s)
Number only	22.8
Number and shape	20.7
Number and size	16.4
Number, size and shape	15.8
Number and colour	7.6
Number, colour and shape	7.1
Number, colour, size and shape	6.4
Number, colour and size	6.1

Source: After Williams, L.G., *Percept. Psychophys.*, 1, 315, 1966.

This is not simply a case of the more factors that are specified, the fewer the items that have to be inspected. The point is that some parts of the specification are more important than others. Table 7.1 shows that whenever the colour of the item in which the desired number lay was specified, short mean search times were achieved. Specifying the colour reduces the items where the number might be to 20% of the total but so does specifying the shape, and yet the latter has much less effect on mean search time. This apparent effectiveness of colour as an aid to visual search is consistent with one of the claimed evolutionary advantage of colour vision, namely, to rapidly detect targets against dappled backgrounds (Mollon, 1989). However, the finding that including colour in the specification of the search item had a major impact on the speed of visual search should not be taken to mean that colour coding is a guaranteed way to enhance visual search performance. If the differences between the colours used by Williams (1966) had been slight, it is doubtful if specifying the colour would have been anywhere near as effective. A more general way to identify what dimension is important is to consider the signal-to-noise ratio between the target items and non-target items, on each dimension. The higher the signal-to-noise ratio on a given dimension, the greater is the importance of including that dimension in the specification of the search item. It is worth noting that the signal-to-noise ratio of colours can be enhanced by the use of a light source with a high gamut area because the colours are then more widely separated in colour space.

Turning now to tasks where the colour of the target is itself meaningful, the choice of light source depends on the degree of colour discrimination required. Where only course discrimination is required, for example, telling red from blue or green, then only light sources with low Commission Internationale de l'Eclairage (CIE) general colour rendering index (CRI), such as the HPS and mercury vapour lamps, will cause confusion about colours (Collins et al., 1986). Where fine colour discriminations are required, for example, when examining colour printing, great care is required in the choice of light source. Recommendations of the light source to be used for fine colour discrimination, in a number of different industries, have been made (IESNA, 2000a). If no specific recommendation is available, then a general rule is that the higher are the CIE general CRI and the gamut area index, the better will be the ability to discriminate colours. The extent to which different light sources will make it possible to discriminate colours can be estimated by using the MacAdam ellipses (see Figure 2.25). Each MacAdam ellipse sets the boundary at which a given percentage of people are able to determine that two colours, one with chromaticity coordinates at the centre of the ellipse and the other with chromaticity coordinates on the ellipse, are just noticeably different (MacAdam, 1942; Wyszecki and Stiles, 1982). MacAdam's ellipses were determined in conditions that offer the maximum sensitivity to colour differences: side-by-side comparison, unlimited observation time, foveal viewing, photopic operation of the visual system and a well-trained observer. Changing any of these factors and adding distracting or confusing stimuli can be expected to increase the difference in colour needed to reach discrimination threshold (Narendran et al., 2000). There can be little doubt that the spectral content of the light source used becomes of increasing importance as the degree of colour discrimination required becomes finer and the outcome of that discrimination is more important for the successful completion of the task.

7.3.2.2 Light Spectra and Achromatic Tasks

At first, it might seem odd to consider what effect light spectrum would have on the performance of an achromatic task particularly after Smith and Rea (1979) failed to find any effect of light spectrum on performance of an early version of the numerical verification task (see Section 4.3.5). In their study, illuminances ranged from about 7 to 2000 lx, and cool white fluorescent, MH and HPS lamps were used as illuminants. Moreover, they studied, in combination with the two lighting variables, the impact of the achromatic luminance contrast and the quality of the visual task as well as the subjects' age. Subjects were in two age groups, younger than 30 years and between 50 and 60 years. Task materials were number lists printed in high- and low-luminance contrast (0.8 and 0.3) and were both typed (8-point type; 12 characters per inch) and handwritten (numbers were approximately the same size and spacing). All subjects were required to find mistakes in these task materials under the different light conditions. Light level, subject age, task contrast and task quality all had statistically significant effects, both in terms of task performance and subjective ratings of difficulty. Light spectrum showed no statistically significant effect for either measure.

However, Berman et al. (1993) showed that light spectrum can influence performance for small, briefly flashed, low-luminance contrast, achromatic tasks, specifically the accuracy with which the orientation of a Landolt ring can be identified. Figure 7.5 shows the proportion of correctly reported orientations for Landolt rings with a gap size subtending approximately 2 min arc at the participant's eyes and presented at four levels of luminance contrast and four levels of background luminance, for two different light sources. One light source was greenish-blue in colour and had a scotopic/photopic ratio of 4.31. The other light source was a mixture of red and pink fluorescent lamps, the combined effect having a scotopic/photopic ratio of 0.24. The marked non-white colour appearance of the light sources used ensures that they are unlikely ever to be adopted for real-life applications. However, they

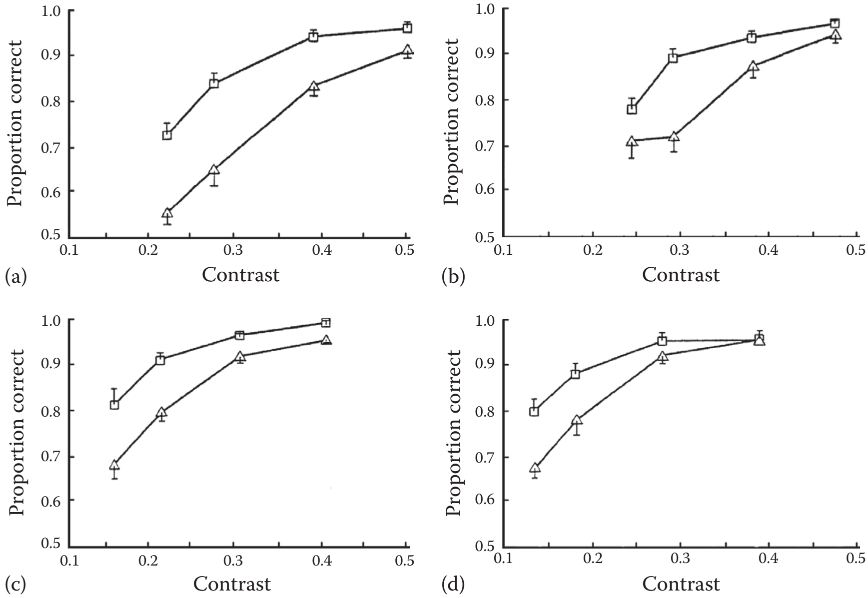


FIGURE 7.5 Means and associated standard errors of the proportion of Landolt ring orientations, presented for 200 ms on a spectrally neutral background, that were correctly identified, plotted against luminance contrast, for four different background luminances: (a) 11.9, (b) 27.7, (c) 47.0 and (d) 73.4 cd/m^2. In all four diagrams, the upper curve (□) is for the blue-enriched greenish-blue illuminant (surround field scotopic luminances = 228 cd/m^2) and the lower curve (Δ) is for the blue-deficient red-pink illuminant (surround field scotopic luminance = 13 cd/m^2). Both illuminants produced a surround field photopic luminance of 53 cd/m^2. (After Berman, S.M. et al., *J. Illum. Eng. Soc*., 22, 150, 1993.)

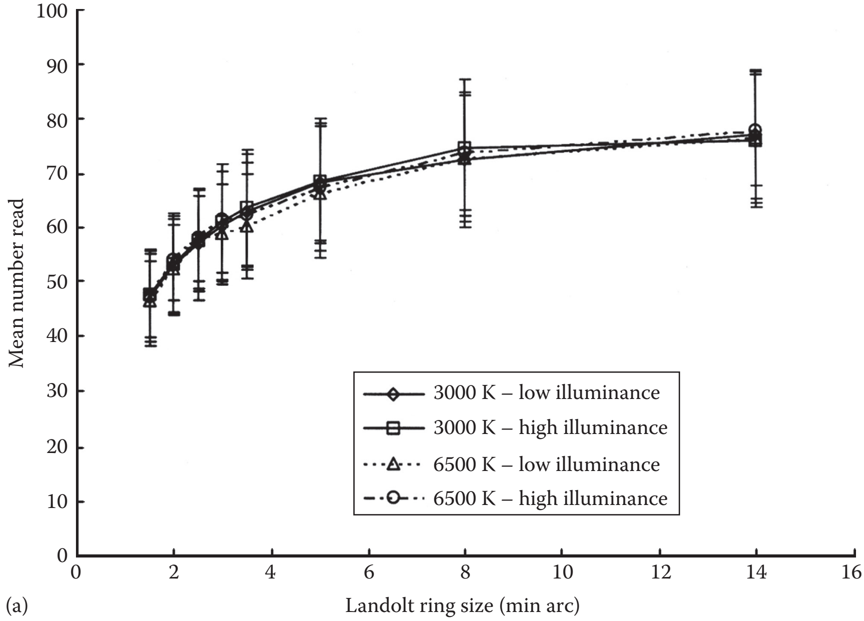
did produce differences in task performance. The blue-enriched, greenish-blue light source consistently has better task performance than the blue-deficient red-pink light source, for different luminance contrasts and background luminances, until the performance reaches the maximum possible. A similar pattern of results has been found for elderly subjects exposed to the same light sources (Berman et al., 1994b).

The proposed explanation of these findings rests on the role of pupil size. Specifically, pupil size in a large visual field is determined predominantly by the response of the rod and ipRGC photoreceptors, even in photopic conditions; the greater the response from these photoreceptors, the smaller the pupil area (Berman et al., 1992; Gamlin et al., 2007). For the light sources described above, the pupil area under the greenish-blue light source was 40% smaller than under the red–pink light source. A smaller pupil area has three effects: it reduces the retinal illumination, it increases the depth of field and it reduces distortion of the retinal image by spherical and chromatic aberrations. The first of these effects, the reduction in retinal illuminance, can be expected to degrade visual performance. The other two, increasing the depth of field and reducing aberrations, can be expected to improve the quality of the retinal image and hence to improve visual performance. All these effects are small, and the trade-offs they produce will depend on the inherent quality of the individual's optical system. An individual who is perfectly refracted will gain little from increasing the depth of field, so might be expected to experience deterioration of visual performance under a light source that produces smaller pupil sizes. However, most people do not have perfect refraction. For these people, the results suggest that light sources that promote smaller pupil sizes can increase visual performance somewhat for achromatic resolution tasks, that is, where the task conditions place it close to threshold, for example, small size, low-luminance contrast and limited exposure time. In the experiment described earlier, the gap in the Landolt rings subtended approximately 2 min arc at the participant's eye, the highest luminance contrast used was 0.4 and the Landolt ring was only displayed for 200 ms.

A number of studies have confirmed the impact of pupil size on visual acuity. Berman et al. (1996) measured word reading visual acuity using different surround luminances of the same spectrum to adjust pupil size. The higher surround luminance produced smaller pupil sizes and better visual acuity. Navvab (2001) measured the visual acuity of young adults at the same illuminance produced by two different fluorescent light sources, one with a low correlated colour temperature (CCT) and one with a high CCT, that is, different light spectra. The high CCT light source, which would have more energy at the short-wavelength end of the visible spectrum, produced the better visual acuity. Berman et al. (2006) measured the visual acuity of school children at the same luminance but using two different fluorescent lamps, one with a CCT of 3600 K and the other of 5500 K. On average, the difference in pupil areas under the two light sources for the small sample of the children taking part in the study was 2.18 mm^2, the higher CCT producing the smaller pupil area. As for the visual acuity, 24 out of the 27 children tested had a better visual acuity under the higher CCT light source.

There can be no doubt that choosing a light source that produces a smaller pupil size leads to a small improvement in visual acuity, a threshold task. Leibel et al. (2010) examined the effect of light spectrum some way above threshold. The task done was reading aloud two-digit numbers. Performance was measured as a combination of the speed and accuracy of reading a fixed number of such numbers. The size and luminance contrast of the numbers were individually adjusted for each participant so that he/she was operating around the knee of their individual visual performance curve, that is, where the subject was sensitive to the visual conditions. Not surprisingly, the results showed that performance on this task was sensitive to both the illuminance on the task and the spectrum of the light used. A higher illuminance and a spectrum that produced a smaller pupil size both increased the performance of the reading task.

The question now of interest is what effect this has for clearly suprathreshold tasks, that is, when the task characteristics are such that the worker is certainly operating on the plateau of the visual performance surface. As noted earlier, the effect of light spectrum on task performance was not apparent in the Smith and Rea (1979) study which used a suprathreshold task. Moreover, Rea et al. (1990) manipulated pupil size over a large range by changing the reflectance and size of the area surrounding the numerical verification task (see Section 4.3.5). They found no statistically significant effect of surround size and reflectance and, thus, pupil size on the performance of the task, a task that was large in size, continuously viewed and presented at two levels of luminance contrast, one low and one high (0.15 and 0.86). Finally, Boyce et al. (2003b)



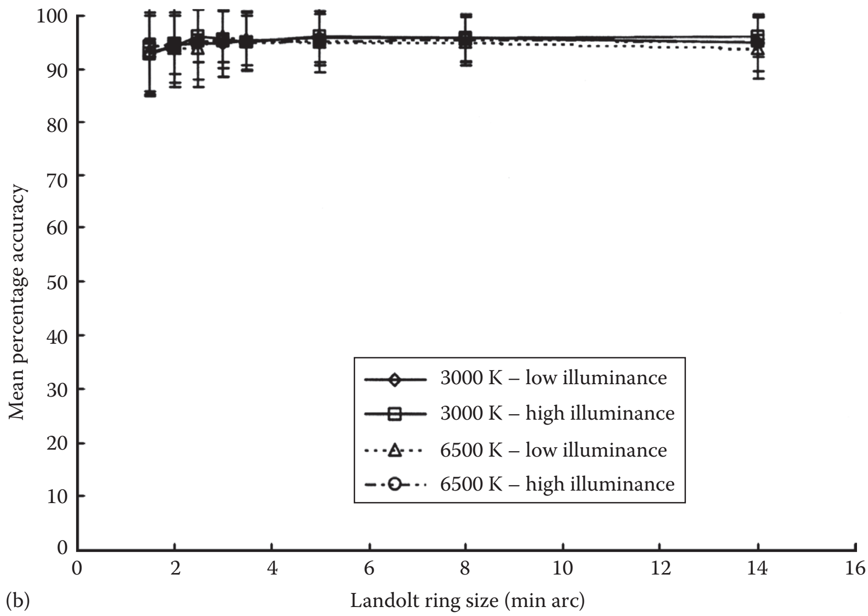


FIGURE 7.6 Means and standard deviations of (a) the number of Landolt rings examined in 20 s and (b) the proportion of Landolt rings of the specified orientation correctly identified, plotted against Landolt ring gap size, for two lamp types with CCTs of 3000 and 6500 K, at 344 and 500 lx. (After Boyce, P.R. et al., *Lighting Res. Technol.*, 35, 141, 2003b.)

tested the hypothesis that light sources that produce smaller pupil sizes ensure better visual task performance at the same photopic illuminance, for both near threshold and suprathreshold conditions, when the task is done under realistic conditions, that is, continuous exposure and free movement of the head. Participants performed a Landolt ring task for eight different gap sizes that, at a viewing distance of 40 cm, subtended 1.5–14 min arc. Other experimental conditions were a high fixed luminance contrast (0.80), two different illuminances (344 and 500 lx) and two lamp spectra covering the range of fluorescent light sources used in offices (CCTs of 3000 and 6500 K). The speed and accuracy of performance of the task were determined by the gap size and, to a much lesser extent, by the illuminance. Lamp spectrum had no statistically significant effect on the performance of the task (Figure 7.6).

To summarize, there can be little doubt that light spectrum operating through pupil size can influence the performance of achromatic tasks that are on the escarpment of the visual performance surface, but it has little effect when the tasks lie on the plateau, especially when the tasks are done under realistic conditions. This does not mean that the choice of light spectrum is irrelevant to the lighting of offices. As mentioned in Section 7.2, the illuminances recommended for office lighting are far above what could be recommended based on visual performance alone. One explanation for this excess is that an office lighting installation has to ensure a high level of visual performance for a wide but unknown range of tasks done by people with a wide but unknown range of visual capabilities. Given this situation, the recommended illuminances can be regarded as providing a safety margin. In this context, it is possible to argue that enhancing visual acuity by choosing a light source that produces smaller pupil sizes would allow the safety margin to be maintained at a lower illuminance, thereby reducing electricity consumption. This argument is being promoted by the US Department of Energy under the slogan of spectrally enhanced lighting. The problem with the argument is that lighting installations have to meet a number of different objectives. Visual performance is certainly one of them but so is providing a satisfactory appearance for people and the space. This is a problem because light spectra that lead to smaller pupils have a lot of energy at the short-wavelength end of the visible spectrum. As a consequence, they tend to have a cool or cold colour appearance. How acceptable this is in offices is still a matter of discussion (see Section 7.3.2.4).

7.3.2.3 Light Spectra and Alertness

Being alert is a prerequisite for the performance of many tasks, particularly those in which nothing much happens for a long time, but when it does, a rapid response is required, for example, monitoring the security camera displays in a shopping centre. The choice of light source is important in such situations because the light spectrum can have a significant influence on the level of alertness. Several studies have shown that exposure to bright light at night enhances alertness as shown by ratings of sleepiness, EEG records of brain activity and measurements of reaction time (Campbell et al., 1995; Cajochen et al., 2000; Lavoie et al., 2003). One possible explanation for such findings is the suppression of melatonin, the hormone associated with sleep. This explanation is supported by studies that have examined the effect of different wavelengths on alertness at night. Lockley et al. (2006) examined the effects of 6.5 h of exposure to equal photon densities of 460 or 555 nm monochromatic light starting at 11 p.m. The results showed that 460 nm light was much more effective than the 555 nm light in reducing feelings of sleepiness, improving reaction times to an acoustic stimulus and modifying EEG power density in a manner consistent with increased alertness. Light of 460 nm is known to be much more effective at suppressing melatonin than light of 555 nm.

However, this cannot be the whole story, for two reasons. The first is that night-time exposure to red light (630 nm), which does not suppress melatonin, has been found to enhance alertness as measured by reduced feelings of sleepiness and changes in the EEG spectrum (Plitnick et al., 2010; Papamichael et al., 2012). The second is that exposure to bright light during the day when melatonin concentration is minimal has also been shown to improve alertness measured by feelings of sleepiness and performance on a vigilance test (Phipps-Nelson et al., 2003). Exactly what the other mechanisms might be is still a matter of discussion, but there are certainly plenty of physiological mechanisms involving the ipRGC photoreceptors available (Ruger et al., 2005; Lockley et al., 2006; Vandewalle et al., 2007). The ipRGC photoreceptors have peak sensitivity at the short-wavelength end of the visible spectrum (see Section 3.2).

While the studies described above are useful for investigating the mechanisms involved in enhancing alertness, they all use narrowband light sources that are unlikely ever to be acceptable for use in conventional offices. Nonetheless, such studies have inspired the development of a fluorescent light source designed to optimize the stimulation provided to the cone and ipRGC photoreceptors while retaining a white colour appearance and a reasonable level of luminous efficacy. This light source has a CCT of 17,000 K and has a spectrum with much more power in the 420–480 nm range than is usual and is consequently called blue-enriched white light. Viola et al. (2008) carried out a field study to examine the effectiveness of the 17,000 K light source relative to a conventional 4,000 K fluorescent light source for improving the alertness, performance and sleep quality of office workers during the day. The study took place on two floors of an office, furnished and laid out in a similar way, undertaking similar work and with similar and limited amounts of daylight. The light sources on the two floors were the 17,000 K lamp or the 4,000 K lamp, each lamp type being used on one floor for 4 weeks before being changed to the other. The mean illuminances produced on the workplaces by the two light source types were 310 lx for the 17,000 K lamp and 421 lx for the 4,000 K lamp. Subjective reports of alertness, performance, fatigue and sleep quality were collected using established questionnaires, once a week, in the morning, around lunchtime and late afternoon. In addition, before starting the exposure to the two light sources, a baseline assessment was carried out under the existing lighting which was the same on both floors. Figure 7.7 shows the change in mean ratings of 94 subjects on scales measuring alertness, performance, evening fatigue and sleep quality from the baseline, after 4 weeks exposure to the two light sources. Despite the lower illuminance delivered by the 17,000 K lamps, it is clear, and statistical analysis confirms it, that exposure to the 17,000 K lamp produces a better response than the 4,000 K lamp, in terms of increased alertness and performance, reduced evening fatigue and better sleep

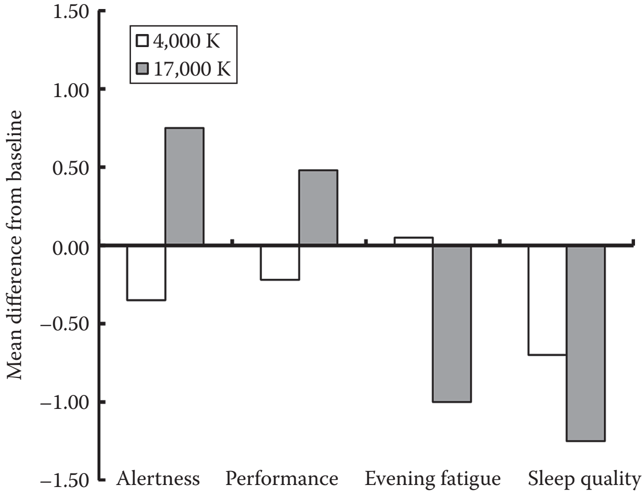


FIGURE 7.7 The mean change from the baseline of ratings of alertness, performance, evening fatigue and sleep quality after 4 weeks exposure to blue-enriched white light (17,000 K) and conventional white light (4,000 K). (After Viola, A.U. et al., *Scand. J. Work Environ. Health*, 34, 297, 2008.)

quality. While encouraging, it is important to note that these changes are small. The scale used for assessing alertness, performance and evening fatigue ranges from 1 to 9 while that for sleep quality ranges from 0 to 21. The magnitude of the effects may also be the explanation for the rather limited impact of 17,000 K lamps relative to 4,000 K lamps found in a field study carried out by Iskra-Golec et al. (2012). In this study, female office workers found the blue-enriched white light to be significantly more energizing than white light, but only in the morning.

To summarize, there is no doubt that exposure to short-wavelength light is beneficial for maintaining alertness at night, but what is not clear is whether this is most efficient means of achieving this aim. Other wavelengths can also enhance alertness at night as can increasing the amount of light. As for exposure during daytime, there is some evidence that blue-enhanced white light can be used to enhance alertness and performance in offices, but, again, whether this is the only means by which this can be achieved seems doubtful. Until all the physiological routes by which alertness is influenced are understood, attempts to tune the light spectrum for alertness seem premature.

7.3.2.4 Preferred Light Spectrum

The appearance of a uniformly lit office will be greatly influenced by its colour scheme. Surface finishes of different colours can produce large changes in the appearance of the office that the choice of light source can modify only slightly. However, the properties of the light source cannot be entirely ignored.

Given that the light source most commonly used in offices is the fluorescent lamp, the range of possible CIE general CRI for office lighting is 50–98, and the range of

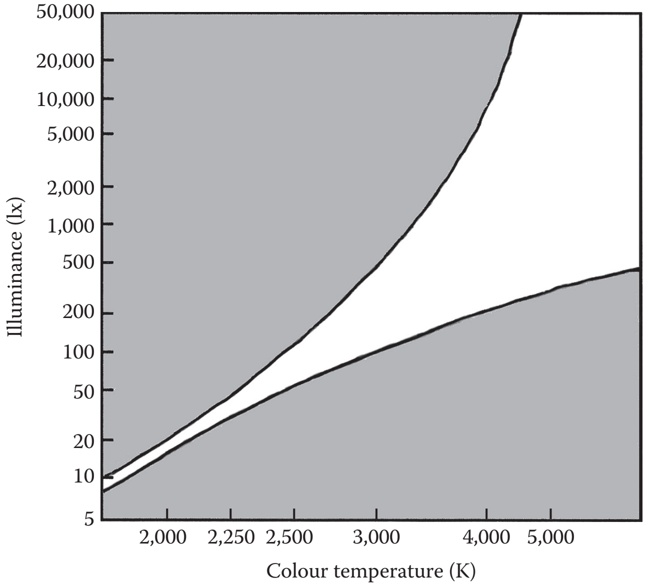


FIGURE 7.8 The Kruithof curve: the white area defines the preferred combinations of the colour temperature of a light source and illuminance. Colour temperature/illuminance combinations in the lower shaded area are claimed to produce cold, drab environments, while those in the upper shaded area are believed to produce overly colourful and unnatural environments. (From Illuminating Engineering Society of North America (IESNA), *The Lighting Handbook*, 9th edn., IESNA, New York, 2000a.)

CCT is between 2,700 and 17,000 K. The question of interest is whether all these fluorescent lamp types are equally acceptable.

The most common answer to this question is that they are not and that light sources with a high CCT should not be used at low illuminances and light sources with a low CCT should not be used at high illuminances. This guidance is based on the work of Kruithof (1941). Figure 7.8 shows a schematic derived from his results. Combinations of illuminance and CCT that lie in the lower shaded area are perceived as cold and drab; those that lie in the upper shaded area are perceived as overly colourful and unnatural. It is only combinations of illuminance and CCT that lie in the unshaded area that are considered to be pleasing. Unfortunately, the work on which this summary is based has not been extensively reported. What is apparent from the details that have been given is that different light sources, incandescent lamps, fluorescent lamps and daylight were used to produce the different CCTs, so it is likely that the light distribution and the colour rendering of the light varied with CCT. As both distribution of light and lamp colour properties are known to affect people's perceptions of an interior, the validity of Kruithof's boundary conditions is open to question.

A direct test of Kruithof's boundary conditions was made by Boyce and Cuttle (1990). They had 15 observers carry out a colour discrimination task in a small, windowless office and then give an assessment of the lighting. The office was lit by fluorescent lamps with virtually the same high CRI value (CRI = 82–85) but very different CCTs (2700–6500 K), producing four different illuminances on the desk (30, 90, 225 and 600 lx) from the same luminaire. From Figure 7.8, it can be seen that, over this illuminance range, the different lamp types should produce a significant change in perception, if Kruithof's boundary conditions are correct. This did not prove to be the case. The major factor in determining the impression given by the lighting was the illuminance. The CCTs had virtually no effect on the observer's impression of the lighting of the room. One plausible explanation for this lack of effect is chromatic adaptation. Each subject experienced each lighting condition for about 20 min before giving his or her evaluation. During this time, the subject's visual system would have adapted to the chromaticity of the light source, an adaptation that would have diminished the difference between the light sources. What this suggests is that for offices, where there is usually plenty of time for chromatic adaptation to occur, the recommendations based on Kruithof's results are unnecessarily restrictive.

As for what happens when there is little time for adaptation, Davis and Ginthner (1990) examined peoples' perceptions of a conference room, lit to three different illuminances (250, 550 and 1250 lx) by fluorescent lamps of similar CRI (89 and 90) but different CCT (2750 and 5000 K). In this experiment, the subjects had only 1 min to adapt to the chromaticity of the light source before giving their evaluation. Nevertheless, the subjective ratings of preference were influenced only by the illuminance and not by the CCT. Han (2002) used a model office to examine the effect of illuminance, CCT and colour tone of decor on the perception of the lighting of an office. As would be expected, she found that illuminance was the major factor determining the perception of brightness and the acceptability of the lighting for an office, but she also found that the use of light sources with a higher CCT produced a perception of greater brightness at the same illuminance (see Section 6.2.2.4). The acceptability of the lighting for an office was also influenced by the CCT, but in this case, it was the CCT that was most commonly used in office lighting practice that was considered most appropriate (4100 K rather than 3000 or 6500 K). Vienot et al. (2009) also examined Kruithof's boundaries using LED clusters mounted in a booth. The LED clusters were used to produce nine different continuous spectra producing three different illuminances (150, 300 and 600 lx) and three different CCTs (2700, 4000 and 6500 K). All the spectra produced CRI values of more than 90. Over 15 min exposure to each combination of illuminance and CCT, participants were asked to do a number of threshold and suprathreshold visual tasks. After doing the tasks, the subjects answered a questionnaire about their perception of the lighting. Figure 7.9 shows the rated pleasantness of the lighting on a 7-point scale (1 = unpleasant, 7 = pleasant). These results show statistically significant effects of both illuminance and CCT on pleasantness but do not support the Kruithof boundary conditions. According to Kruithof, the 6500 K light source should be most pleasant at 600 lx, while the 2700 K light source should be the most pleasant at 150 lx. However, these results show that the 6500 K light source is the least pleasant at all three illuminances and the 2700 K light source is the most pleasant at both 150 and 600 lx.

A similar pattern of dislike for a 6500 K light source was found in a field study by Akashi and Boyce (2006). This study examined whether it was possible to reduce illuminances in an office by one-third without causing complaints, using higher CCT

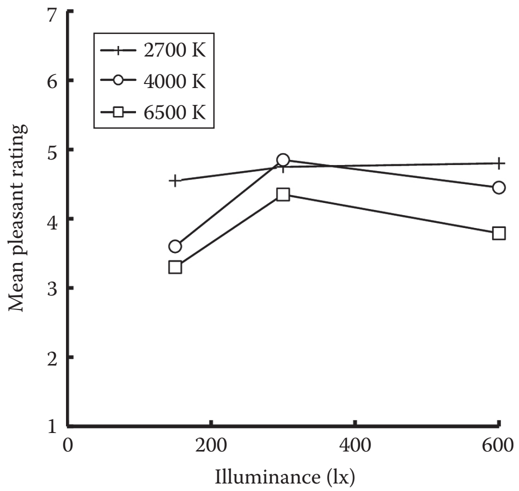


FIGURE 7.9 Mean ratings of pleasantness for lighting producing three different illuminances and three different correlated colour temperatures. The rating is made on a seven-point scale, 1 = unpleasant, 7 = pleasant. (After Vienot, F. et al., *J. Mod. Opt*., 56, 1433, 2009.)

light sources or sparkle elements to enhance the perception of brightness. It was found that using fluorescent lamps with a CCT of 6500 K rather than 3500 K avoided the perception of gloom when a lower illuminance was used, but when the illuminance was maintained at about 500 lx, the 6500 K lamp was considered too cold for an office. It was concluded that the highest CCT suitable for an office where the illuminance was more than 350 lx was 5000 K.

By now, it should be clear that there is a lot of variability in people's responses to different light spectra that lead to different CCTs. About the only consistent result is that high CCTs tend to be considered unpleasant when high illuminances are used. Whether or not this finding holds for countries where high CCT (5000 and 6500 K) lamps are routinely used in offices, for example, Japan, remains an open question. Other questions concern the effects of the visual demands of the work, for example, does the work require resolution of fine detail in which case a high CCT may be useful for the improved visual acuity it may ensure (see Section 7.3.2.2) and what is the skin tone of occupants? The appearance of your skin is important because it carries messages about health. Quellman and Boyce (2002) made a study of the preferred CCT for people with different skin tones using one incandescent, five compact fluorescent lamps (CFL) and one metal halide lamp. All these lamps had a CRI in the range 80–82, except for the incandescent which had a CRI of 100, and CCTs in the range 2700–5000 K. In one condition studied, these lamps provided an illuminance of 450 lx on the hand, typical of that used in offices. Subjects were divided into four skin types based on descent: European; Chinese, Japanese and Thai; Indian and Sri Lankan; and African American. It was found that there was no one lamp type that was preferred by all subjects. But over all subjects, the most preferred lamp was a CFL with a CCT of 3500 K. The incandescent lamp with a

CCT of 2780 K and the CFL with a CCT of 5000 K were both disliked, the subjects wishing to avoid either an excessively florid or pale appearance.

The aforementioned studies have examined CCTs up to 6500 K. However, fluorescent light sources with CCTs up to 17,000 K are now available. One field study claims that the 17,000 K lamps used were well liked (Viola et al., 2008) something that is inconsistent with the results described above. However, in their field study, Iskra-Golec et al. (2012) found that blue-enriched white light was considered less pleasant than white light over the working day. Such findings suggest the potential for many contextual factors to influence the preference when there is no clear basis on which to make a judgement. If this view is correct and the variability in the results discussed earlier suggests it is, then it implies that light source CCT is a minor factor in determining satisfaction with the lighting of an office. The illuminance provided is much more important. As for the light source CRI, there is no doubt that choosing a light source with a CRI above 80 will tend to produce more saturated surface colours and a perception of greater brightness and visual clarity (see Section 6.2.3). There is equally no doubt that choosing a light source with a CRI below about 65 will be unsatisfactory because of the non-white colour appearance of the lighting. Given that all that is required is to avoid light sources with a CRI below 65, then there is a wide range of acceptable light sources which can all be preferred by different groups of people, in different countries, in different contexts.

Although the discussion earlier has been in terms of the colour properties of the light source, it is important to appreciate that the impact of these properties may be modified by the colour content of the office decor. This is because the spectral content of the light reaching the eye is a combination of the light received direct from the luminaires and the light received after reflection at the surfaces in the interior. Mizokami et al. (2000) showed that when the colour of walls, floor and furniture were orange, subjects perceived a room to be illuminated by incandescent lamps though it was actually illuminated by fluorescent lamps of a higher CCT. The colour content of the office may also influence satisfaction with the lighting. Boyce and Cuttle (1990) showed that introducing natural colour, in the form of fruit and flowers, into what was essentially an achromatic space enhanced the positive impressions created by the lighting, particularly at high illuminances.

Taken together, these findings support the view that provided the light source has a CRI above about 65 and its chromaticity coordinates are close to the Planckian locus so that it can be called a nominally white light source, almost any light source will be acceptable for office lighting. Given that a number of different light sources are acceptable, the choice between them is best made on the basis of the application. If the work involves accurate colour judgements, then a light source with a high CRI is desirable. If accurate colour judgements are not part of the work, then the choice should be made after taking into account the effect of the lighting on the office decor and the message it sends, as well as the occupants' experience and expectations of office lighting. Where care is necessary is where a low illuminance is being proposed because then the perception of greater brightness associated with high CCT light sources may be valuable or where a very warm or very cool decor is proposed, in which case a light source CCT that offsets the warmth or coolness of the decor would be appreciated (Han, 2002).

7.4 LIGHTING SYSTEMS

By choosing a lighting system, the lighting designer determines the distribution of light in the office and hence such aspects of visual discomfort as glare, veiling reflections and shadows (see Section 5.4). In addition, the distribution of light has an influence on the perception of the office (see Section 6.3). One of the major differences in perception is whether the office is perceived to be primarily lit by daylight or by electric light. As a rule of thumb, any office where the average daylight factor is more than 5% will be perceived as daylit, and the electric lighting will not be needed during the daytime. Conversely, any space where the average daylight factor is significantly less than 2% will be perceived as electrically lit, even in daytime and daylight will only be noticeable on room surfaces close to the windows (SLL, 2009). What the average daylight factor is will depend on the architecture of the space and the daylight delivery system used.

7.4.1 Daylight Delivery Systems

Daylight can be delivered into an office through conventional windows, clerestory windows or skylights, as well as a number of remote distribution systems, such as light shafts, ducts and pipes (Tregenza and Wilson, 2011). By far the most common is the conventional window. Windows have the advantage of providing both daylight to the interior and a view-out. Their disadvantage is that the amount of daylight delivered to the office decreases dramatically as the distance from the window increases, although the view-out is preserved over a large distance. Clerestories, which are essentially windows mounted high up close to the ceiling, are one way to improve this situation, but they suffer from the disadvantage that the view-out is then limited to the sky. Skylights offer the possibility of delivering daylight over the whole of the office, but again, the view-out is limited to the sky. In addition, skylights only effectively deliver daylight to the room immediately beneath them. This is not a problem for a single-storey building, but for multiple storeys, the only alternatives are either windows in the outside walls or a light shaft or light pipes of some sort, and these latter are notoriously inefficient.

The important aspects of windows as far as people are concerned are their size, shape, spectral transmittance and solar shielding. Ne'eman and Hopkinson (1970) examined the minimum acceptable size of window using a model open-plan office through which observers could look at real views. The observers were asked to adjust the window width to give the minimum acceptable window size. It was found that they could do this consistently except when the window was uniformly bright and featureless. For more usual views, the minimum acceptable window size was determined by the amount of visual information provided by the view, near views requiring larger window sizes than far views. The judgement of minimum acceptable window size was not much influenced by the amount of daylight or sunlight that was admitted to the model, by the interior illuminances or by the position of viewing the window. These findings, together with the fact that observers could not make consistent adjustments when the window was featureless, suggest it was the view-out that was determining the minimum window size. About 25% of the window-wall

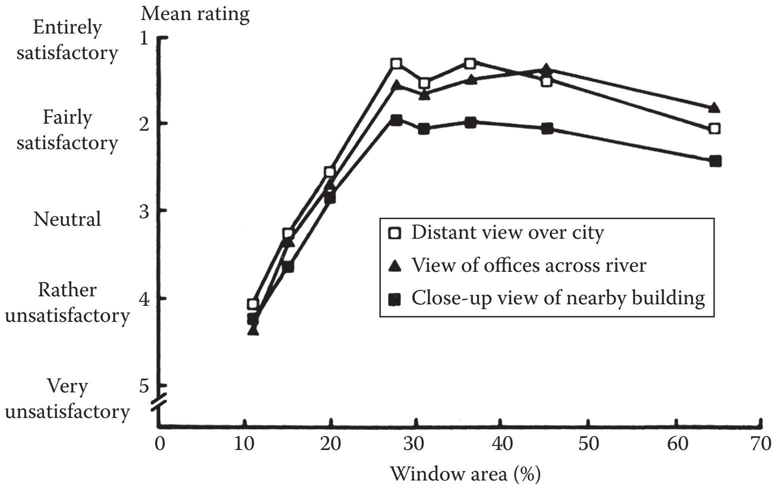


FIGURE 7.10 Mean ratings of satisfaction with windows for different window areas and views. The window area is expressed as a percentage of the window-wall area. (After Keighly, E.C., *Build. Sci.*, 8, 321, 1973a.)

area was the minimum acceptable window size for 50% of observers, rising to 32% if 85% of people were to be satisfied.

Keighly (1973a) also measured the response to window size. Using a model of an open-plan office, 40 observers were shown a range of windows that differed in size (11%–65% of the window-wall area) and in the number and layout of apertures. Through these windows, a number of different views were presented on film. The observers were asked to rate their satisfaction with the windows on a five-category scale. Figure 7.10 shows the mean ratings of satisfaction for single windows of different sizes for the three views used. From Figure 7.10, it can be seen that glazed areas of 15% or less of the window-wall area are considered unsatisfactory, but above 30%, almost complete satisfaction occurs. These results are in reasonable agreement with those of Ne'eman and Hopkinson (1970), although the importance of the type of view is much less, possibly because of the static and limited nature of the views used by Keighly.

Keighly (1973a) also examined the effect of dividing a given glazed area into different numbers of apertures. This produced some very marked differences. People disliked the use of several windows of different sizes, a large number of regularly arranged narrow windows and wide mullions. The common characteristic of these aspects of window design is that they break up the perception of the view. In general, people preferred windows to be large, regularly arranged and horizontal.

The preference for horizontally orientated windows is in disagreement with the conclusions of Markus (1967) who found a preference for vertically orientated windows. Keighly (1973b) again used a model open-plan office to examine the preferred window shape. Specifically, a rectangular window covering 20% of the window-wall area was adjusted until it was in the preferred position and of the preferred shape. The most frequently preferred condition was a central horizontal aperture, with the elevation being determined by the skyline of the view, until the skyline approached the level of the ceiling. The views used were predominantly orientated horizontally which suggests that the shape of the window was being treated as frame for a view. Ludlow (1976) reached the same conclusion. Using a similar apparatus to Keighly, he asked 20 observers to adjust a window aperture to the preferred shape and size for the view. He concluded that the specific view did have a large effect on the preferred size and shape.

Ludlow (1976) also found that the preferred window size was between 50% and 80% of the window wall, values that are much higher than those considered satisfactory by Keighly's observers. This difference may have been simply the difference between what is satisfactory and what is preferred or it may have been due to differences in the views from the models. Nonetheless, the basis for the usual practice in temperate climates of having window sizes somewhere between 20% and 40% of the window-wall area is clear. Below 20% of the window-wall area, dissatisfaction with the windows is likely to arise, particularly if they are concentrated into one or two large areas so that many people do not have a view at all. Above 40% of window-wall area, satisfaction with the window size will be high, but unless care is taken to control the admission of sunlight, the probability of thermal or visual discomfort will increase.

It is important to appreciate that these results have all been collected from people who are used to a temperate climate. It is at least plausible that people who feel daylight is rationed, for example, the inhabitants of countries such as Finland, and those who have an excess of daylight, for example, the inhabitants of India, would have different preferences. Also, it is worth noting that these results have been obtained in the context of an office. Preferences for window size may be different in other contexts (Butler and Biner, 1989).

As for spectral transmittance, there are two aspects that need to be considered, the total transmittance of light and the colour appearance of the light transmitted. Boyce et al. (1995) used a model office to examine the acceptability of different total transmittances for three types of glass with different spectral transmittances, when looking at a real scene under clear and overcast skies, from an interior lit to either 500 or 1000 lx. The window size was fixed at 42% of the window-wall area. Figure 7.11 shows the percentage of observers finding glazing acceptable for use in an office plotted against the percentage transmittance. Two conclusions can be drawn from Figure 7.11. The first is that percentage transmittances above about 50% are highly acceptable but that as the percentage transmittance decreases, percentage acceptance also decreases. The second is that the major factor determining acceptability is the visible transmittance but there is some variation associated with the spectral transmittance of the glass, the nature of the sky and the illuminance of the office.

Before accepting the results from Figure 7.11 as gospel, it is important to appreciate that they have a number of limitations. The first is the short time, only a minute or two, for which each window condition was viewed. The second is that the measurements were all taken during the middle part of the day. The third is that measurements were not taken when the sun was incident on the window. The fourth is that all the measurements were made in a temperate climate. The short time for viewing means that the levels of acceptability for different transmittances are representative of the subjects' immediate reaction on entering a room. This is important because decisions about whether to switch on electric lighting in a daylit room are frequently based on

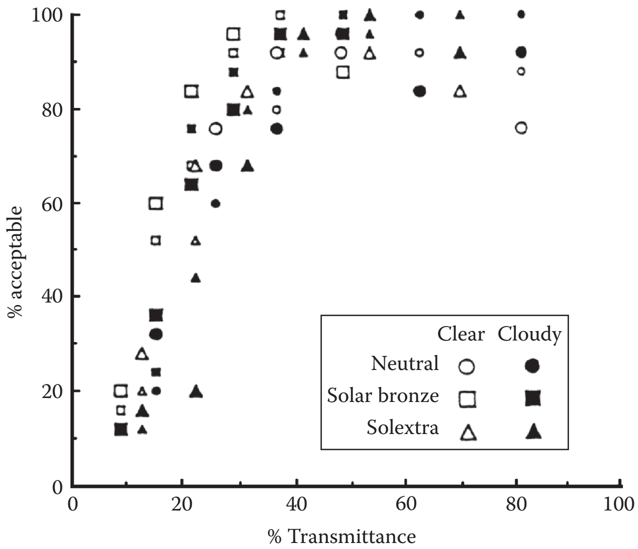


FIGURE 7.11 Percentage of observers considering the glazing acceptable, plotted against the transmittance of the glazing, for three glass types, under clear and cloudy sky conditions. The filled symbols indicate a cloudy sky; the open symbols, a clear sky. The larger symbols of each type are for the 1000 lx interior illuminance, and the smaller symbols are for the 500 lx interior illuminance. (After Boyce, P. et al., *Lighting Res. Technol*., 27, 145, 1995.)

the minimum illuminance experienced when first entering the room (Hunt, 1979). However, it is undeniable that much longer exposures might change the minimum glazing transmittance that is acceptable, although whether minimum glazing transmittance would increase or decrease depends on whether sensitization or habituation occurred. The fact that the measurements were taken in the middle part of the day is a limitation because it could be argued that low-transmittance glazing has its largest effect around dawn and dusk, because it effectively shortens the day, particularly on dull, overcast days. It seems likely that a glazing transmittance that is just acceptable at midday would not be acceptable around dawn or dusk. The fact that measurements were only taken without the sun being incident on the window is not much of a limitation because when the sun is visible through a window, the tendency is to use blinds to mask the sun (Rubin et al., 1978; Rea, 1984) in which case the glazing transmittance is irrelevant. Finally, the fact that the measurements were taken in temperate climates implies a certain attitude to daylight. In high northern or southern latitudes, where daylight is in short supply for part of the year, the minimum acceptable transmittance will probably be increased, while in latitudes close to the equator where daylight, and particularly sunlight, is plentiful and needs to be controlled, the minimum acceptable transmittance will probably be decreased and a decrease in acceptability of high glazing transmittances may occur. These predictions about the effects of latitude are matters of conjecture. It would be interesting to determine if they are true or false.

There can be no denying that there is a lower limit to the transmittance of glass used in windows if the glazing is to be acceptable. There are also limits on the colours of the glass that are acceptable. Glass is available in several different tints,

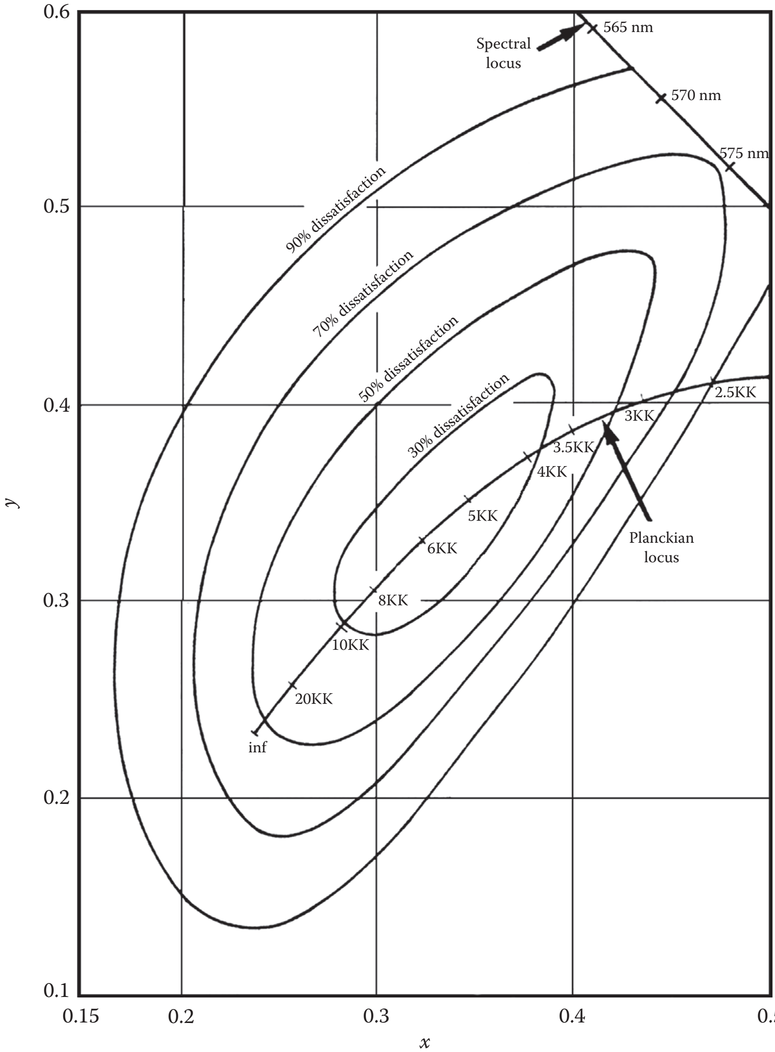


FIGURE 7.12 Percent dissatisfaction contours for the chromaticity of glazing plotted on the CIE 1931 (*x*, *y*) chromaticity diagram. (After Cuttle, C., *Lighting Res. Technol.*, 11, 140, 1979.)

typically, bronze, green, blue and grey, the tint often being chosen for architectural reasons rather than anything to do with the effect on the visual conditions inside the building. Cuttle (1979) examined the limits of tinting of glass used for windows. Figure 7.12 shows the dissatisfaction contours for glass to be used in windows for daylighting, based on judgements of people sitting in a room lit by light transmitted through a window filled with a liquid filter that could be continuously varied over a wide range of colours. From Figure 7.12, it is clear that glass types with chromaticities that depart from the central part of the Planckian locus risk being considered unsatisfactory by a significant number of people.

Any daylight delivery system also needs to be considered in terms of its solar shading because solar shading can have an impact on both the visual and thermal environment. The impact on the visual environment is through the admission of sunlight to the office. The impact on the thermal environment is through the heat gain and heat loss of the whole building and, locally, on the likelihood of thermal discomfort caused by overheating due to excessive thermal radiation (sunlight) or overcooling, due to radiant heat loss to a cold window or the generation of draughts. Markus (1967) found that 86% of the people in the 12-storey office he studied preferred sunlight in the office all the year round, but there was a tendency for those who sat nearest to the windows to be less enthusiastic about it than those who worked further away. Ne'eman et al. (1976) claimed a similar result. Over the four different office buildings they studied, there was a strong emphasis on the desirability of sunlight, but there was also a clear underlying complaint about visual and thermal discomfort. The strength of the complaints depended on the facilities for controlling the visual and thermal environment. Where blinds were available and the air-conditioning was adequate, few complaints were heard. Where there was no means to control sunlight falling on the working area or where the air-conditioning system was inadequate, complaints were common.

Clearly, there are multiple factors that determine the acceptability of a window as a daylight delivery system, and all of them should be considered when designing windows. But it would be as well not to stop there. Butler and Biner (1989) found that the factor most strongly predicting peoples' preferences for window size was the view-out for temporal information. Other aspects of the view-out were also closely correlated with the preference for window size. This finding emphasizes the need to evaluate any window design in two directions, for its effect on the lighting of the interior and for its impact on the view-out. Both these aspects need to be satisfactory for a window design to be considered satisfactory.

Not all offices are suitable for windows. Some are constructed within a building and have no outside wall, while others are so deep that even when there are windows, the amount of daylight reaching the interior is minimal. In these situations, light pipes, or ducted daylight guidance systems as they are also known (CIE, 2006a), are a possibility. These systems consist of three components: a collector, a light guide and a distributor. The collector is an optical system mounted of roof or wall designed to collect light from the sky and sun. The collector can be passive or active, the active form involving some form of sun tracking. Light from the collector is inserted into the light guide which is usually a hollow pipe lined with very high reflectance material, although solid optic material relying on total internal reflection can be used (Zhang and Muneer, 2002; Callow and Shao, 2003). The light guide takes the light to the distributor which is where the light is emitted into the office. The effectiveness of such systems can be quantified by the daylight penetration factor, this being the illuminance delivered to a point in the office expressed as a percentage of the exterior illuminance. What the daylight penetration factor is that it can vary widely depending on the performance of all three components but particularly on the length and number of turns in the light guide. Carter and Al Marwaee (2009) report a survey of fifteen multi-person offices, seven being windowless while in another four, the windows were so remote as to deliver no daylight to the workplaces. All the offices were fitted with tubular daylight guidance systems as well as electric lighting systems. Surveys showed that while the tubular

TABLE 7.2
Percentage of Occupants of Deep Open-Plan Offices Fitted with Tubular Daylight Guidance Systems, with or without Windows, Who Liked the Visual Environment Provided, Who Could Detect Variations in the Weather and Time and Who Thought the Majority of the Light Reaching Their Workplace Was Daylight

Daylighting	Liking the Visual Environment	Detecting Weather Variations	Detecting Approximate Time	Thinking the Majority of Light Is Daylight
With windows	60	75	58	37
Without windows	27	22	29	6

Source: After Carter, D.J. and Al Marwaee, M., *Lighting Res. Technol.*, 41, 71, 2009.

daylight guidance systems were capable of delivering a significant amount of daylight to the workplaces, the occupants of the offices were reluctant to regard their output as daylight. This is evident in Table 7.2 which shows the percentage of occupants working in offices with windows and without windows liking the visual environment and the external view, being able to detect weather variations and the approximate time as well as thinking that the majority of light reaching their workplace is daylight. Examination of Table 7.2 suggests that tubular daylight guidance systems are not an adequate substitute for windows. Indeed, Carter and Al-Marwaee (2009) recommend that where tubular daylight guidance systems are used, some windows should be provided, wherever possible, to aid the occupants' contact with the outside, even when they fail to deliver any meaningful amount of daylight to the working area. These results also imply that the distributors of daylight guidance systems should be designed so as to make them clearly different from the electric lighting luminaires.

7.4.2 Electric Lighting Delivery Systems

Electric lighting delivery systems used in offices consist of luminaires of different types arranged in different ways. By far the most common layout is the regular array designed to provide a uniform illuminance across the whole of the assumed horizontal working plane. Such regular arrays are popular because they allow the occupants of the office to arrange the furnishing however desired with the confident expectation that the illuminance will be similar everywhere. Given the frequency with which office layouts are changed in some rapidly expanding industries, the fact that there is no need to rearrange the lighting every time the furniture layout is changed is valued as one less thing to worry about.

Another constraint on office lighting delivery systems is the maximum lighting power density set by some authorities (see Section 16.3). Such limits more or less exclude the use of some possible lighting systems from widespread use because they cannot provide the required illuminances without exceeding the lighting power density limit. Examples of currently excluded systems are cove lighting and luminous ceilings. Even when there is no legal limit on lighting power density, there is a *de facto* limit set by expectations about how much it will cost to run an electric lighting system. Most businessmen will be reluctant to pay much more than usual to operate an overhead, literally and financially.

The luminaires used in regular arrays can be classified into three types: direct, indirect and direct/indirect. A direct luminaire is one in which all the light is emitted below the horizontal plane where the luminaires are located, usually the ceiling. An indirect luminaire is one in which all the light is emitted above the horizontal plane where the luminaire is located, usually a plane some distance below the ceiling, the luminaire being suspended from the ceiling. A direct/indirect luminaire emits light both above and below the horizontal plane where the luminaire is located. Of course, these simple classifications are not absolute. Luminaires are assigned to one or other class according to where the majority of their light is directed. Some indirect luminaires have a perforated metal lower plate to give the luminaire some brightness, so some light is emitted below the horizontal plane. Provided the amount emitted downwards is less than about 10% of the total luminaire light output, the luminaire can still be classified as an indirect luminaire. A similar consideration applies to the direct/indirect luminaire. It is not really appropriate to classify a luminaire as a direct/indirect luminaire unless the minimum light output above or below the horizontal plane is more than 10% of the total light output from the luminaire. Care should also be taken with advertising claims. One type of ceiling-recessed luminaire is marketed as a recessed indirect luminaire because there is no light emitted directly from the lamp, all the light emitted being first reflected from the interior of the luminaire. Calling such a luminaire indirect is misleading. The light distribution from a regular array of such luminaires recessed into a ceiling is virtually identical with that produced by a regular array of direct luminaires fitted with a prismatic lenses.

Regular arrays of direct, indirect and direct/indirect luminaires can give very different appearances to an office. The appearance produced by a regular array of direct luminaires depends on the luminous intensity distribution of the luminaire and their spacing. The narrower is the luminous intensity distribution, the closer the luminaires have to be placed to each other and the more vertical is the flow of light. Such an installation will produce a lot of light on the horizontal working plane but very little on any vertical plane, especially the walls. Further, the only light that reaches the ceiling does so by reflection from the other surfaces in the room. There are two risks with such an installation. The first is that the office will appear as gloomy and rather cave-like. The second is that the there is a strong possibility of uncomfortable shadows and veiling reflections occurring. This emphasizes another point that a luminaire is a complete package, and not just in its mechanical form. It is almost always a mistake to select a luminaire on the basis of one criterion alone. It is much better to consider all the possible impacts of a luminaire on the visibility of the task and the appearance of the office before making a selection.

As for indirect lighting, this effectively uses the ceiling as a large area, low-luminance luminaire. To avoid reflected images of the inside of the luminaire being formed, ceilings used with indirect lighting are almost universally diffuse reflectors with the result that the distribution of light in an office lit by an indirect lighting installation tends to be diffuse. Thus, the walls are almost always well lit, as is the working plane. Further, diffuse lighting means that shadows are few and veiling reflections very slight. Although such conditions are unlikely to be considered uncomfortable, they may not do much to make the office attractive. In terms of the lighting quality classifications laid out in Section 5.6, indirect lighting is an almost infallible means to achieve indifferent lighting.

Direct/indirect lighting is a compromise between direct and indirect lighting, but it is a good compromise in that it avoids the worst features of both. The indirect component softens any shadows and veiling reflections and provides some light on the walls. The direct component provides stronger modelling and offers some relief from the boring uniformity of indirect lighting.

It should not be thought that direct/indirect lighting is the only means to avoid the disadvantages of direct or indirect lighting alone. One alternative that is frequently advocated for its energy-saving potential is task/ambient lighting. In this, the ambient lighting is usually provided by a regular array of some sort and each individual workstation has a task light. Task lights can take several different forms, from the fixed under-shelf lighting commonly found in cubicle furniture systems to free-standing luminaires that allow the light source to be positioned in a wide range of positions. All task lights can be switched but some also allow dimming. The energy-saving potential arises from the possibility that the ambient lighting, which is designed to light the space rather than the task, can be set to a lower illuminance than recommended for office work, for example, 200 lx, relying on the task light to bring the illuminance in the task area up to the required level. When the ambient lighting alone provides the recommended illuminance on the workstation, any task lighting is seen as a supplement rather than a replacement, and the energy savings are likely to be slight (Newsham et al., 2005). Even if this is the case, flexible task lighting has other advantages. It provides an element of individual control of lighting and can be used to reduce any shadows or veiling reflections in the work area (Japuntich, 2001). Another means of addressing the low wall illuminances produced by direct lighting is to use wall-washing or by placing the luminaires close to the wall, although the latter may still cause a problem if the sharp cut-off of the direct luminaire produces a shadow at the top of the wall. As for indirect lighting, some accent lighting of features in the office or some decorative lighting can go some way to make the space more interesting.

7.4.2.1 Preferences

It is now appropriate to consider if there is clear preference between one type of electric lighting delivery system and another. Harvey et al. (1984) had people perform a task for an hour and then give ratings for various aspects of the quality of the direct and indirect lighting systems used. The two indirect lighting systems were clearly preferred over the direct lighting system, using a recessed parabolic luminaire. Leibig and Roll (1983) and Roll (1987) examined people's reactions to direct, indirect and direct/indirect lighting while reading text on paper and on a computer screen. For paper-based work, there were no statistically significant differences in the assessment of the installations. For the computer-based work, the direct and the direct/indirect lighting installations were considered much better than the indirect lighting installations. Hedge et al. (1995) carried out an evaluation of a building where the renovated offices were lit by either indirect or direct lighting. In this case, there was a clear preference for the indirect lighting. Further, it was observed that 1 year after the lighting was installed, the occupants had modified much of the direct lighting by disconnecting or removing lamps, whereas the indirect lighting was virtually untouched. Houser et al. (2002) carried out a systematic examination of the perceptions of the same room lit by a regular array of suspended luminaires. The luminaires were manipulated to form totally direct, totally indirect and several forms of direct/indirect lighting, all forms delivering an illuminance of 538 lx on the horizontal working plane. The differences in preference for the various forms of lighting were small, but what preference there was favoured direct/indirect lighting with an indirect component of at least 60%. Boyce et al. (2006b) had people working in a simulated office for a day under either direct lighting or direct/indirect lighting or direct/indirect lighting with a switched desk light. Seventy-one percent of subjects considered the direct lighting to be comfortable, 81% thought the direct/indirect lighting with switched desk light was comfortable and 85% thought the direct/indirect lighting alone comfortable. Other studies of ambient/task lighting have produced very different degrees of satisfaction (Newsham et al., 2005). This is probably because of the large number of ways task lighting can be implemented. The obvious conclusion to be drawn from these studies is that there is a preference for direct/indirect lighting, probably because such lighting provides direct illumination of both the task and the space and softens any shadows and veiling reflections.

7.4.2.2 Performance

Another possibility is that the distribution of light in the room can change task performance. If this could be shown to be true, then there would be a real reason for choosing one type of electric lighting delivery system over the others. There are two reasons why the distribution of light in the room might be expected to change task performance. The first is that different distributions of light in the room may make the task more or less visible because of different illluminances on the task, shadows, disability glare or veiling reflections and hence affect task performance directly. The other is the possibility that different distributions of light in the room will produce different perceptions of the space which, in turn, will influence the mood of the subject and hence affect the motivation to perform the tasks.

Harvey et al. (1984) had people perform a task involving checking lists of numbers printed on paper against a similar list displayed on a computer screen, under direct and indirect lighting. There was no difference in the performances of the task for the different lighting systems.

Newsham et al. (2005) had people doing a number of office tasks in a windowless office for a day lit either by a regular array of direct lighting or by the same array with task lighting. A typing task in which the subject had to enter three 300 word passages into the computer was done 24% faster when task lighting was available. While this was almost certainly due to the task lighting producing a higher illuminance on the page which had to be typed, that is, increased visibility, there was also an improvement in the performance of a task requiring vigilance when task lighting was available, something that may have been due to mood.

Veitch and Newsham (1998a) measured the performance of an array of computer-based tasks, done by a large number of temporary office workers, over a full working day, in a large windowless office furnished with individual cubicles. On each day, the office was lit by one of nine different lighting installations classified according to three levels of power density and three levels of perceived lighting quality. The low-quality lighting installations consisted of a regular array of direct, prismatic luminaires. The medium-quality installations used a regular array of direct parabolic luminaires. The high-quality installations used various arrangements of indirect or direct/indirect luminaires, sometimes suspended from the ceiling and sometimes furniture-mounted. The low lighting power density installations all used an adjustable task light and an under-shelf task light. The medium and high lighting power density lighting installations did not use any form of task lighting. The subjects were able to discriminate between the lighting installations. When the office was lit by direct lighting systems, it was considered as brighter than when it was lit by indirect lighting systems, and lighting conditions that included task lighting and lower ambient illuminances were considered as less bright and less glaring than lighting systems that did not have task lighting. As for task performance, a complex pattern of interactions was obtained, with some tasks being performed better under one lighting installation and others under another. Most of the changes in task performance were small (1%–3% of variance explained). Interestingly, the strongest effect any visual condition had on the performance of any task was for the change of screen polarity on a typing and a proofreading task. Changing the screen type from negative polarity (bright text on a dark background) to positive polarity (dark text on a bright background) explained 7%–9% of the variance in task performance, probably because the higher background luminance of the positive polarity screen made the display less subject to interference from reflected images of the rest of the room. This is a direct effect lighting on task visibility.

One limitation of this study is that the different lighting installations produced different illuminances and different light distributions on the paper tasks and on the computer screen which may have changed the visibility of the tasks. This makes it difficult to determine the extent to which changes in visibility or changes in the perception of the space are responsible for any changes in task performance. A study by Eklund et al. (2000) avoided this problem. They had temporary office workers work for 8 h doing a data-entry task in three private, windowless offices, all with the same decor and furniture. Three different lighting installations were used, one in each office. All three lighting installations provided a similar illuminance on the task, without veiling reflections or disability glare, so for the same task, they provided similar task visibility. However, the three lighting installations were very different in light distribution over the room, ranging from very uniform indirect lighting to very concentrated overhead lighting. There was no difference in performance of the task under the three lighting installations. Somewhat more surprisingly, there was no difference in the workers' perceptions of the three lighting installations, despite the opinions of lighting experts that the lighting installations clearly differed in quality. However, changes in point size of the material to be entered, and hence in task visibility, did produce statistically significant changes in task performance.

Eklund et al. (2001) had people perform the same data-entry task for 4 h, but this time, they always had the same lighting installation with the same light distribution, but with two different levels of decor. In one condition, the office was bare and achromatic. In the other, some colourful decor was added to the room. Again, there was no difference in task performance between the two decors, although the subjects did perceive the chromatic decor as more colourful, attractive and interesting. Again, changes in the task visibility created by changing print size, luminance contrast or illuminance on the task did produce statistically significant changes in task performance.

These studies clearly demonstrate that changes in task visibility can be reliably expected to change the performance of visual tasks but the effects of differences in the perception of the lighting of the space are much less certain. There are several reasons why this might be so. One is that perhaps people naive in lighting are much less sensitive to lighting conditions that do not affect task visibility or visual comfort than lighting experts, in the same way that wine connoisseurs are more sensitive to wine characteristics than are people who do not drink wine frequently. If people are not sensitive to changes in lighting conditions that do not affect task visibility or visual comfort, then it is unlikely that changes in such conditions will change their mood and hence their motivation to perform the task. Another is that given a long enough exposure to lighting conditions that do not affect task visibility or visual comfort, people habituate to them and so the conditions become of less and less significance to them and hence less and less likely to change their mood. Another is that the range of lighting conditions may have not been extreme enough, although the three lighting installations used in Eklund et al. (2000) were selected to cover the extremes of current lighting practice. Finally, it might also be important that the data-entry task focused attention on a small area in that all the information needed to do the task was available in that small area. The rest of the room contained no information relevant to the task, so the lighting of the rest of the room was irrelevant to the worker. There is little doubt that for tasks in which there is information spread over many different parts of the room, the light distribution over the whole room will matter, but that will be because the light distribution then affects the ability to extract the information required to do the task, that is, it affects task visibility. Despite all this speculation, there is one conclusion that is clear. This is that lighting distributions that do not affect task visibility or cause visual discomfort are not certain to affect task performance. They may, because light distributions can also affect the mood and motivation of the office worker or they may alter the message sent by the lighting and this message may in turn alter behaviour (see Section 4.2). Unfortunately, there are many other factors besides lighting that can affect mood and message, and light distribution may be of little importance relative to these other factors. More research is needed.

7.4.2.3 Lighting and Electronic Displays

Over the last 30 years, office work has moved from being almost entirely based on paper to being heavily dependent on electronic displays, although any count of the number of printers and copiers in use will indicate that paper-based tasks are still common. This widening of activity from paper alone to paper plus electronic displays has led to the design of luminaires with luminous intensity distributions that take into account the physical properties of displays. There are a number of such properties that differentiate electronic displays from paper. First, the display is usually positioned in a vertical or near vertical plane, although this is becoming less common with the advance of mobile devices. Second, the display is self-luminous, which means it can be seen in an unlit room. Third, being self-luminous means that increasing the amount of light from the room falling on the display decreases the visibility of the display. Therefore, to enhance the visibility of the display, it is necessary to control the incidence of light from the room onto the display, which usually means reducing the illuminance on vertical planes. The result of such an analysis was a rash of recommendations concerning the light distribution of luminaires suitable for use with displays. These recommendations took two forms. For direct lighting, the recommendations limited the luminance of the luminaire in specified directions, usually above angles of 55° or 65° from the downward vertical. For indirect lighting, the recommendations consisted of a maximum average luminance and a maximum peak luminance of the ceiling. For direct/indirect luminaires, both forms of recommendation applied. The objective of both these forms of recommendation was to limit the luminance of the reflected image of the luminaire or ceiling seen in the display. The recommendation for direct lighting assumed that the luminaires were mounted in a ceiling, and the display was in a vertical or almost vertical plane. If either of these two assumptions was incorrect, then limiting the luminance of the luminaire above 55° or 65° would be of little value.

Before accepting any recommendations, it is a good idea to consider what lies behind them. The basis of these luminaire recommendations lies in the effect light incident on the display has on the display's visibility. Light incident on a display can have three undesirable effects: reduce the contrast of the display, increase competition for the users' attention between the display and the reflected images and cause changes in accommodation due to the fact that the display and the reflected images are at different distances from the observer (Boyce, 1991; Rea, 1991). The key to avoiding these problems is to reduce the luminance of the reflected images relative to the luminance of the display. None of the published guidance explicitly stated the basis of the recommendations, but one of the most influential sets of data was that of Leibig and Roll (1983). They asked people to identify the borderline between distracting and non-distracting reflections in displays generated on screens with different reflection properties. The luminance of the reflections was varied by changing the luminance of the luminaire being reflected. The luminance identified as representing the borderline between disturbing and non-disturbing reflections for each subject was used to calculate the percentage of subjects who would find a given luminance non-disturbing, that is, who would be satisfied with the display. Figure 7.13 shows the percentage of people satisfied with the display for various display polarity/screen reflectance/lighting type combinations plotted against the luminance of the luminaire that is reflected in the display. By comparing the results for the same display, bright characters on a dark specularly reflecting screen seen under two forms of lighting, direct and predominantly indirect lighting, it can be concluded that an acceptable luminaire luminance for one lighting installation will not necessarily be acceptable for another. By comparing different displays, bright characters on a dark screen and dark characters on a bright screen, both seen on screens with specularly reflecting surfaces lit by predominantly indirect lighting, it can be concluded that negative polarity displays (dark characters on a bright background) are less sensitive to reflections than positive polarity displays (bright characters on a dark background). By comparing the results for the most sensitive conditions, the specularly reflecting, positive polarity display seen under predominantly indirect lighting, with the least sensitive condition, the diffusely reflecting, negative polarity display seen under direct lighting, it can be

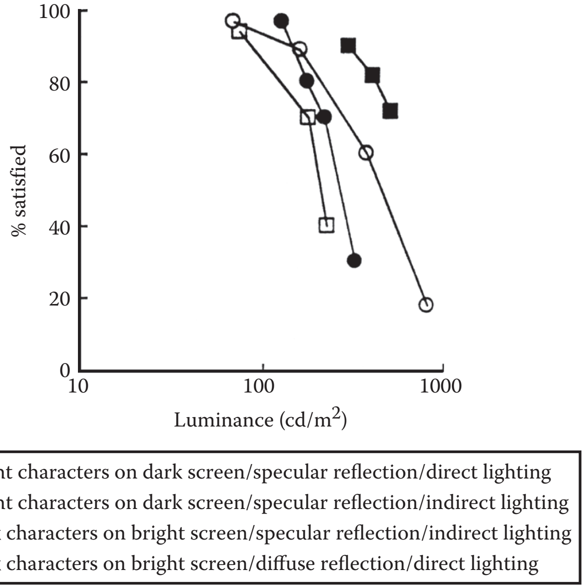


FIGURE 7.13 Percentage of people satisfied with the display plotted against the luminance of the luminaire that is reflected in the screen. Data are given for both positive and negative polarity displays on screens with different reflection properties seen under different lighting conditions. (After Leibig, J. and Roll, R.F., Acceptable luminances reflected on VDU screens in relation to the level of contrast and illumination, *Proceedings of the CIE 20th Session*, Amsterdam, the Netherlands, CIE, Paris, France, 1983.)

seen that what constitutes an acceptable luminaire luminance can vary widely, for example, from 130 to 500 cd/m^2 for 80% of the observers. From these data, Leibig and Roll recommended a maximum luminaire luminance of 200 cd/m^2 in any direction that will lead to a reflection from a visual display screen.

There were two unfortunate outcomes of these developments. The first was that regular arrays of the direct lighting luminaires designed to meet the recommended luminance limits produced a gloomy effect in many interiors with the walls and ceiling being underlit. This led many observers to conclude that the cure was worse than the disease. As a result of this experience, together with the finding that reflections considered disturbing had no effect on the performance of visual tasks requiring the use of the display (Kubota and Takahashi, 1989), recommendations have become more flexible. This is evident by the fact that the maximum luminaire luminance limit can now range from 200 to 1500 cd/m^2 depending on the polarity of the display and the reflection characteristics of the screen (SLL, 2005).

The second unfortunate outcome was the belief that it is only by changing the lighting that the problems of reflections in a display can be overcome, although it is evident from Figure 7.13 that the reflection characteristics of the display are also important in determining the degree of disturbance. This implies that problems of screen reflections can be minimized by changing the screen type. When this work was done, slightly curved CRT displays were common. Today, flat screen displays using liquid crystal display (LCD), LED and plasma technology are common, and CRT displays have largely disappeared. Different display technologies can have very different reflection characteristics (Howlett, 2003). Lloyd et al. (1996) attempted to address the problem of focusing solely on the lighting by developing a quantitative model to predict observer's ratings of how disturbing the reflections on a display were from a set of photometric measurements of both the luminaire and the display. The three variables that were used to predict the observer's response were the luminance contrast of the display under the lighting installation; the luminance contrast of the reflected image of any source of high luminance, such as a luminaire or window; and the width of the blur function, that is, the degree to which the reflection from the display is blurred. For the lighting installation, the parameters that have to be measured are the luminance of the source that is seen by reflection in the display, the luminance of the background to that source and the illuminance incident on the display. For the display, the parameters to be measured are the minimum and maximum luminances in the absence of any room lighting, the diffuse and specular reflection properties of the display, the proportion of the display at the maximum luminance and the blur width. These parameters are all that is needed to calculate the three variables in the model. The three variables were combined into an equation that explained 85% of the variance in a set of ratings of disturbance for reflections seen in both CRT and LCD displays.

One limitation of this model is the fact that it does not take into account the size of the luminaire. Howlett (2003) points out that the blur characteristic of the screen will have a much greater impact on the image of a small luminaire than a larger one. For a small luminaire, the blurred image will be larger but has a lower maximum luminance and lower luminance gradient. For a large luminaire, the blurred image will still be larger but the maximum luminance will be little changed. Ramasoot and Fotios (2012) made an extensive series of measurements of the level of disturbance experienced by people looking at displays using CRT, LCD and plasma technologies, in both positive and negative polarities, and ranging from laptops to whiteboards. Figure 7.14 shows the mean disturbance ratings for the seven screen types examined when reflecting different luminances of two light sources subtending 1° and 10° at the eye of the observer. These results demonstrate that the level of disturbance is influenced by the type of display and the size and luminance of the reflected light source; the larger the size and the higher the luminance, the more likely is the disturbance. From these data, Ramasoot and Fotios (2012) constructed a model of the disturbance rating that should occur for some combination of source luminance and size and screen characteristics. This model is given by the empirical equation:

$$\text{Rating} = 10.277 - 22.263\, r_s - 1.515\, \log L_A + 0.083\, H + 0.0014\, L_B - 45.255\, W$$

where

ρ_s is the specular reflectance of the screen for the size of the light source

L_A is the source luminance (cd/m^2)

H is a measure of blur

L_B is the background luminance of the screen (cd/m^2)

Ω is the solid angle that the reflected light source subtends at the viewing position (sr)

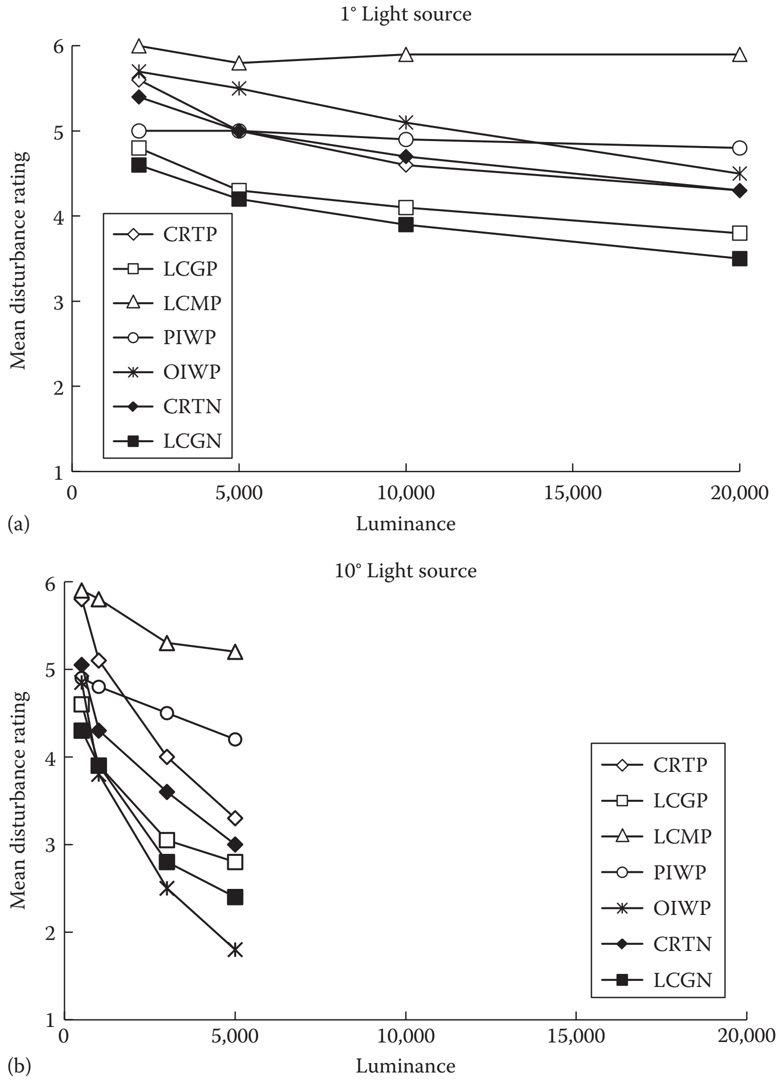


FIGURE 7.14 The mean disturbance rating for seven displays plotted against source luminance for two source sizes (a) 1° and (b) 10°. The seven display types are CRTP (CRT screen in positive polarity), CRT screen in positive polarity; LCGP, LCD gloss screen in positive polarity; LCMP, LCD matte screen in positive polarity; PIWP, front projection whiteboard in positive polarity; OIWP, overlay plasma whiteboard in positive polarity; CRTN, CRT screen in negative polarity; LCGN, LCD gloss screen in negative polarity. The disturbance rating was made on a six-point scale with 1 = very disturbing and 6 = not at all disturbing. (After Ramasoot, T. and Fotios, S.A., *Lighting Res. Technol.*, 44, 197, 2012.)

The disturbance is expressed on a six-point scale with 1 = very disturbing and 6 = not at all disturbing. This model explains 85% of the variance in the underlying rating data.

As well as ratings of disturbance, direct measurements were made of the source luminance at which the reflected image in the display became just disturbing. From such measurements, a model for predicting the borderline source luminance, defined as the source luminance at which only 5% of observers found the reflected image disturbing, that is, 95% found it acceptable, was developed. The model is given by the empirical equation:

$$\text{Log}\, L_S = 3.013 - 10.668\ r_s + 0.043\, H + 0.001\, L_B - 4.550\ \mathtt{W}$$

where

L_S is the borderline source luminance (cd/m^2)
ρ_s is the specular reflectance of the screen for the size of the light source
H is a measure of blur
L_B is the background luminance of the screen (cd/m^2)
Ω is the solid angle that the reflected light source subtends at the viewing position (sr)

This equation explains 86% of the variance in the measured log borderline source luminance.

Such models can be used to identify the level of disturbance likely to occur with a given luminaire and screen combination, to identify luminaires suitable for use with a given screen type or to determine the screen type that can be used with a given lighting installation. However, to do this requires some careful photometric measurements, measurements that are only likely to be within the capabilities of display and luminaire manufacturers. But is all this trouble worthwhile? Technology has dramatically increased the screen luminances available and the flexibility with which the display can be positioned. Further, everyday observation suggests that many office workers are indifferent to screen reflections and, if reflections do cause a problem, are quite capable of adjusting the geometry to deal with it. What this suggests is that special equipment and standards for offices where many displays are used, which are all of them, are no longer necessary. All that is required is for the designer to be aware of the possibility of screen reflections, to be able to identify the screen characteristics most likely to produce disturbing reflections and then to be able to identify what to do about it. This last point can be met either by changing the screen or the lighting. If changing the lighting is what is necessary, then it is possible to use the model described earlier to determine the borderline source luminance and apply that when selecting a luminaire.

7.5 LIGHTING CONTROLS

Lighting controls are installed in offices to reduce energy use and/or to provide a means of adjusting the lighting conditions to ensure individual comfort. The control of daylighting is usually continuous in that window blinds allow variations in the amount of light admitted and the view-out. Electric lighting controls can be either discrete or continuous in that the light sources can either be switched or dimmed. The controls can also be automatic or rely on the occupants' actions. How effective and how useful lighting controls are depends on their ease of use and how satisfactory occupants find the outcome. Automatic controls require minimal human intervention, once they have been commissioned successfully, but they may not always produce satisfactory outcomes. Manual controls require human intervention and also may not produce a satisfactory outcome.

7.5.1 Window Lighting Controls

7.5.1.1 Manual Window Controls

The manual controls applied to windows are usually some form of blinds: Venetian, vertical, roller, etc. One reason blinds are provided is to enable people to eliminate the discomfort experienced when they have a direct view of the sun or a bright sky. When blinds are not provided, it is not unknown to find pieces of paper taped to the window at positions where a view of the sun occurs. But the use of blinds is more than just a simple open/shut operation. Maniccia et al. (1999), in a study of private offices in the United States, found that people adjusted the slant angle of their vertical blinds to occlude the sun and to allow daylight to enter while preserving a view-out; in other words, they adjusted the blinds to optimize the performance of the window. Further, the pattern of blind use was different on the different sides of the building. Figure 7.15 shows the average percentage of time with the blinds in each position for offices on the four sides of the building. Clearly, the blinds are most frequently closed on the south and west sides of the building, less often closed on the east side and rarely closed on the north side. This pattern is consistent with the exposure to the sun over the working day.

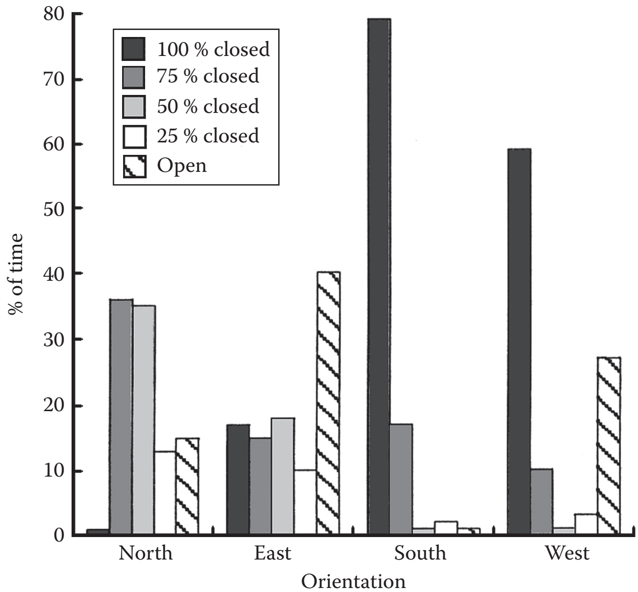


FIGURE 7.15 The average percentages of time window blinds were in four categories of position for five different window orientations. (After Maniccia, D. et al., *J. Illum. Eng. Soc.*, 28, 42, 1999.)

Another aspect of manual blind control that supports the importance of sun exposure has been observed. This is the frequency and timing of blind adjustment. Rubin et al. (1978) examined the use of blinds in 700 private and two-person offices in the United States. They found that daily blind manipulation was rare, most offices having blinds set to a fixed position for long periods, this position being designed to restrict sunlight entering the office. Rea (1984) found a similar pattern in an office building in Canada. However, when Lindsey and Littlefair (1993) examined blind use in five office buildings in England, they found that the frequency of blind manipulation in different offices ranged from never to daily. Where blinds were frequently adjusted, this was usually in response to the arrival of the direct sunlight on their window. This led to a lowering of the blind, a position in which the blind remained until the end of the working day or even until the next morning. Clearly, individuals attach very different priorities to having daylight and a view-out relative to all the other aspects of work. Some have a strong preference for daylight and are prepared to spend time adjusting the blinds to give them the desired conditions. Others are less zealous and, knowing what to expect as the Earth rotates, prefer to leave the blinds in a position where they know sunlight will not cause them discomfort at any time of the day or even year.

This observation should not be taken to mean that blinds do not matter. Blinds should be considered as an essential component of a window system. They provide a necessary means to control the lighting provided by the window so that people can achieve the daylighting conditions they prefer, whatever they may be. Certainly, people value window blinds just as much as the windows themselves (Maniccia et al., 1999).

7.5.1.2 Automatic Window Controls

Automatic window controls are rare despite the existence of suitable technologies ranging from electrochromic glazing to motorized blinds. Further, what work has been done on the use of automatic window controls has concentrated on their impact on energy use and the structure of the control system either in isolation or integrated into a control system that operates both daylight and electric lighting. One of the few studies that have looked at people's reaction to an automatic window control system is that of Reinhart and Voss (2003). They measured the occupant's behaviour and the environmental conditions in six private and four two-person offices in Germany, for about 8 months. The electric lighting in each office consisted of indirect lighting manually switched. Daylight was provided through a large window fitted with two sets of horizontal Venetian blinds separated by a light shelf. The automatic control system lowered both sets of blinds when the illuminance on the façade of the building exceeded 28,000 lx and raised them when the illuminance dropped below 28,000 lx. When lowered, the blinds below the light shelf had the slats closed, but the slats of the blind above the light shelf were kept horizontal so as to direct light deeper into the room. The automatic blind control system could be overridden by manual control at any time. When the manual override was used, the automatic system was disabled for 2 h. The most interesting result of this extensive study was that 6393 blind adjustments were made during the 174 weekdays measured. Of this total, 3005 (47%) were automatic adjustments and 3388 were manual (53%). Of the manual adjustments, 1352 occurred within 15 min of an automatic adjustment and were classed as a correction of the automatic system. Further analysis showed that 88% of the manual corrections were made to raise the blinds after the automatic control system had lowered them. Clearly, people are very reluctant to have their blinds lowered automatically when they considered it unnecessary. There was much less reaction to raising the blinds automatically, an automatic raising only being overridden when a weak winter afternoon sun penetrated deep into the office. This unsatisfactory pattern of use may have been simply because the illuminance chosen to control the automatic system was wrongly set. Reinhart and Voss (2003) suggest that the number of manual overrides would have been reduced if two different façade illuminances had been used, 28,000 lx for raising the blinds and 50,000 lx for lowering the blinds. Whether or not this would have been effective is unknown, but it does serve to reveal the fundamental nature of the problem. This is that lowering blinds automatically takes away something of value to many people, that is, daylight and a view-out. To do this on the basis of something as simple as an illuminance on a façade without any consideration of the effect on the visual environment as experienced by the occupant of the office is asking for trouble. What is needed is a much more sophisticated sensing of when the occupant of the office wants the blinds to be lowered. This might be done by some form of adaptive control system that learns how the occupant uses the blinds, but such a system adds expense and complication. Until attention is given to matching automatic window control systems to people's wishes, it is unlikely that such systems will be widely used.

7.5.2 Electric Lighting Controls

7.5.2.1 Manual Electric Lighting Controls

The most common form of manual lighting control is the switch-by-the-door. Ideally, manual switching should be used to ensure that the electric lighting is on only when there is someone present and daylight is not available. Unfortunately, as in so many other human activities, this ideal is rarely achieved. Crisp (1978) reported a series of field observations of the patterns of lighting switching in multi-occupant offices in the United Kingdom. He found that the lighting was only switched at the beginning and end of the working day; it was rarely switched in the middle of the day, a pattern also found in California by Rubinstein et al. (1999) and in Germany by Reinhart and Voss (2003). However, Crisp (1978) also found that in a classroom, switching was most likely to occur at the beginning and end of each period of occupation, something that occurred several times a day. What this suggests is that the probability of switching will be related to the social organization of the space. In the multi-occupied office, it is likely that no one was willing to take responsibility to switch off the lighting while there were still people in the office, while in the classroom, the teacher took the responsibility to switch the lighting on and off. This observation can be considered as a difference between public and private lighting. Public lighting is lighting serving several people, and switching the lighting will affect all of them. There is a social inhibition against switching the lighting because of the potential for aggravation. Private lighting is lighting serving only one person or a group of people where one person is clearly in charge. In this situation, the lighting may be considered the property of the individual in charge. It is likely that switching will occur much more frequently in private lighting than in public lighting situations.

However, even in a private office, where one person is clearly in charge, there is no guarantee that manual switching of lighting will always occur. Love (1998) found a wide range of switching behaviour in private offices that was more a characteristic of the occupant than of the daylighting conditions. For the same daylight conditions, one occupant rarely used the electric lighting, and others kept the electric lighting on for most of the working day, while yet others switched the lighting according to the amount of daylight available. It is clear that switching behaviour is driven by many factors besides the photometric conditions.

One factor that definitely affects switching behaviour is the ease of understanding what luminaires are controlled by what switches (Crisp, 1978). Where the layout of the switches bears no obvious relationship to the layout of luminaires, or where the switch panel is not even in the same room as the luminaires it controls, the probability of switching is low. The message of these observations is simple. To ensure that lighting will be switched off when not required, make the switching simple to do. Put the switch panel where anyone operating it can see the luminaires being switched; put a plan of the luminaire layout and the switches adjacent to the switch panel; and wire the luminaires to the switch panel so that all the luminaires controlled from a single switch are receiving similar amounts of daylight.

It might be thought that one way to encourage switching in a multi-occupied space is to convert public lighting to private lighting by giving each luminaire its own switch. Boyce (1980) observed such an installation, in which each luminaire was fitted with a pull-cord switch. These were little used. This was partly because the pull-cords were not easily accessible to some of the occupants and partly because the luminaires were not often located directly above someone's desk. Again, this is a matter of public and private lighting. What is considered private depends on the location of the luminaire relative to the user's workspace. Pull-cord switches and more modern variants such as wireless or infrared (IR) remote controls are most likely to be used when the luminaire is directly above the desk and hence can be considered private lighting.

Given that electric lighting is most likely to be switched when someone enters an office, what is it that determines whether a person will use the switch-by-the-door to turn on the electric lighting? The answer appears to be the amount of daylight in the working area of the office when the person enters. Hunt (1979) carried out a series of field studies of patterns of lighting switching in deep-plan offices and the photometric conditions at the time of switching. He found that the probability of the lighting being switched on when entering a room was closely related to the minimum illuminance on the working plane (Figure 7.16). Specifically, the probit curve fitted through the data took the form

$$y = \frac{-0.0175 + 1.0361}{[1 + \exp(4.0835(x - 1.8223))]}$$

where

$100y$ is the percent switching probability

$x = \log_{10}$ (minimum daylight illuminance in working area in lux)

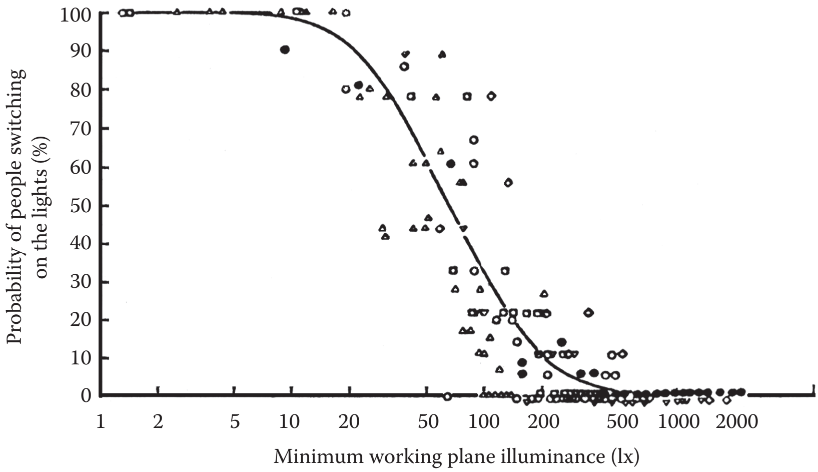


FIGURE 7.16 The probability of people switching on the lighting on entering a room plotted against the minimum illuminance on the working plane at the time of entering the room. (After Hunt, D.R.G., *Build. Environ.*, 14, 21, 1979.)

According to this equation, the probability of switching on is 100% when the minimum illuminance is 7 lx, is 0 at 658 lx and is 50% at a minimum illuminance of 67 lx. Reinhart and Voss (2003) found a similar group response to switching on the lighting on arrival, although there were wide individual differences. Such information allows for estimates to be made of the number of hours for which electric lighting is likely to be operated in daylight spaces where manual switching is used (Lynes and Littlefair, 1990). It also suggests an opportunity for a simple energy-saving system in daylight spaces. Such a system involves a simple time switch that turns off the electric lighting at a time when there is a lot of daylight available, say at noon. Given that there is a lot of daylight, it is unlikely that anyone will trouble to switch on the electric lighting until dusk so energy will be saved (Hunt, 1980). Such a system represents a positive use of human inertia.

Although switches are still the most widely used means for controlling office lighting, dimming technology and wireless networks have opened up the possibility that individuals in both private and in multi-occupied offices could be given control of the illuminance in their working areas. A number of studies have been made of the way in which office workers use such manual dimming controls. The first thing to say is that people tend to use such controls in a rational way. Boyce et al. (2000a) conducted a laboratory study of how temporary office workers doing a variety of tasks in small, private, windowless offices used a hand-held dimming control. Measurements showed that the workers choose lower illuminances when working at a computer than when doing the same task on paper. This is rational because for paper-based work, increasing the illuminance increases the visibility of the task materials, while for the self-luminous computer screen, increasing the illuminance reduces the luminance contrast of the display.

The second thing to say is that, given individual control of illuminance on their workplace, people choose a very wide range of illuminances. Figure 7.17 shows the

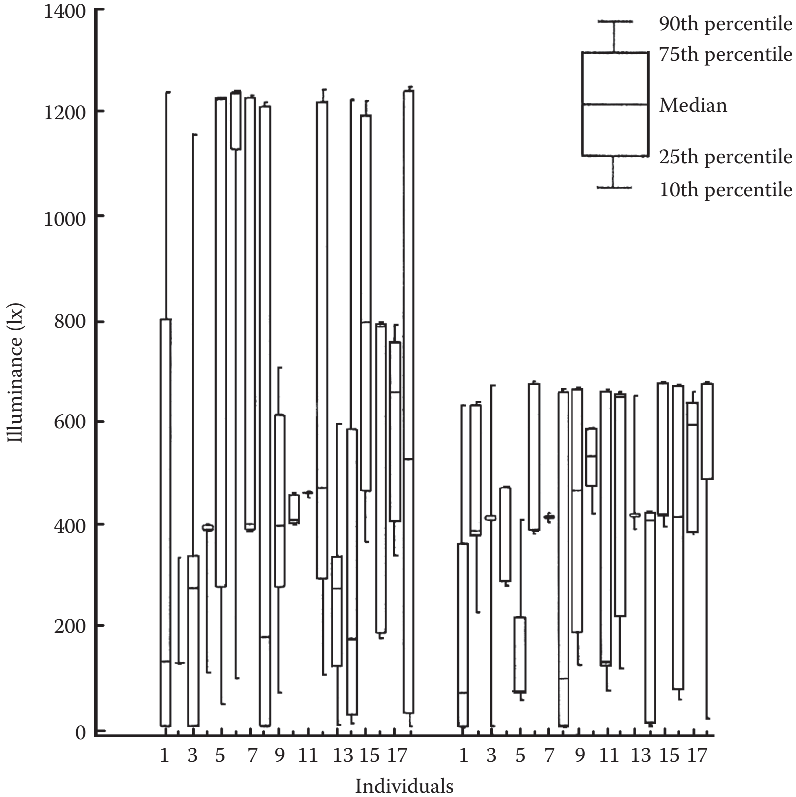


FIGURE 7.17 The range of illuminances chosen by 18 subjects carrying out a number of different office tasks in a private office for a day and having available a hand-held device for dimming the lighting. Two different offices were used, one with a maximum illuminance on the workstation of 1240 lx and the other with a maximum illuminance of 680 lx. (After Boyce, P.R. et al., *J. Illum. Eng. Soc.*, 29, 131, 2000a.)

range of illuminances chosen by the subjects during the day. Four facts are apparent from Figure 7.17. First, some subjects use the dimming control a lot while some rarely use it at all. Second, different subjects have very different preferences for illuminance. Third, many of the subjects prefer a lower illuminance than that commonly used in offices (500 lx). Fourth, the illuminances selected depend on what range of illuminances is available. This last point implies that any hope of saving energy by giving people control of the lighting is dependent on the choice of the maximum illuminance installed. Boyce et al. (2006a) provide some support for these findings and offer some evidence for a suitable maximum illuminance. They carried out a study in which temporary office workers worked for 1 day in a multi-person simulated office furnished with cubicles and with only a small amount of daylight. One lighting condition studied allowed the occupant of a cubicle to adjust the illuminance on the desktop over a range 250–1175 lx. Measurements made in the afternoon after the workers had had some experience of what was possible showed the expected wide range of chosen illuminances and that many chosen illuminances were below current office lighting recommendations. Further analysis showed that if a fixed illuminance is required, then a desktop illuminance of 400 lx is the illuminance that will ensure that the highest percentage of people are within 100 lx the illuminance they prefer (see Figure 7.3). It was also shown that for an installation with individual dimming control, a maximum illuminance of 700 lx would allow 90% of people to achieve their preferred illuminance.

While these studies are interesting, they are limited by the short time for which the subjects worked in the office (1 day). A longer-term field study of different forms of lighting controls, including manual dimming, has been made by Maniccia et al. (1999) in a building containing mainly private offices. The most obvious difference in the use of the dimming control was the frequency with which the dimming control was used. In Boyce et al. (2000a), the participants used the dimming control about 8–10 times a day. In Boyce et al. (2006a), most participants only adjusted the lighting at the start of the day. In the Maniccia et al. (1999) field study, the participants made an average of one dimming adjustment every 3.9 days. Some of this difference in frequency of use can be attributed to the novelty of having the dimming control; a new toy has to be played with. Another factor is the range of visual difficulty of the tasks undertaken; a large range will encourage the use of illuminance adjustment. Of these three studies, the field study is most likely to reflect the way in which people use individual dimming control in the real world. This means that after the novelty of having control has worn off, people use the dimming control to adjust the illuminance to the level they prefer for the sort of tasks they expect to do, and once that is established, they use the dimming control rarely. Despite the infrequency of use, it is important to recognize that people do value having individual control. Boyce et al. (2006b) showed that having individual control increased the percentage of people finding the lighting comfortable to 91%, from the 71% found for fixed direct lighting.

7.5.2.2 Automatic Electric Lighting Controls

There are three common forms of automatic lighting controls: time switches, photosensor dimming and occupancy sensors. Time switches are simple to install and commission. What they do is to switch the electric lighting between states at set times. The states most commonly used are simply on and off, although intermediate levels are sometimes used. Time switching (also known as scheduling) is a valuable means of reducing energy waste in buildings where there is a consistent pattern of use making it possible to predict when lighting will not be needed.

Photosensor dimming (also known as daylight harvesting) involves an automatic control system, consisting of a photosensor, a control algorithm and a dimming ballast, that dims the electric lighting as the amount of daylight increases. In principle, such a system can ensure significant and sustainable reductions in electrical energy consumption (Lynes and Littlefair, 1990; Rubinstein et al., 1999). However, there are four factors that make it difficult to achieve these savings in practice. First are the wide differences in individual preferences for illuminance. In multi-occupied spaces, the individual who likes the most light is likely to be the first to complain about the electric lighting being dimmed. Facility managers dislike occupant complaints and so will usually increase the illuminance at which dimming starts, thereby reducing the potential for energy saving. Second, inertia in the use of window blinds used to control glare from the sun and sky means that the daylight available may be less than expected. Third, the commissioning of the control system is not simple (Rubinstein et al., 1997) partly because of the frequently unknown control algorithm of the system (Bierman and Conway, 2000). Fourth, photosensor dimming systems are not cheap. There is an interesting paradox in that the more efficient the electric lighting system becomes and hence the less energy there is to be saved, the more difficult it is to justify the cost of an elaborate control system. What all these mean is that photosensor dimming systems need to be applied with care if they are to be successful.

Occupancy sensors (also known as motion detectors) are probably the most widely used automatic electric lighting controls. Using either passive IR or ultrasonic technology, they detect movement in a space. Passive IR sensors can only detect movement within the direct line of sight. Ultrasonic sensors can detect movement out of the line of sight. For both technology types, if no movement is detected over a fixed time, the electric lighting is switched off, or sometimes set to a dimmed condition. Conversely, if movement is detected, the lighting is automatically switched on. Occupancy sensors use different technologies, provide different coverage areas, have different sensitivities to movement and can be arranged to have different combinations of automatic/manual and on/off actions. The human inertia about lighting conditions evident in the use of window blinds suggests that the automatic-off/manual-on arrangement is likely to save more energy than any other combination.

All three forms of automatic electric lighting control have the potential to eliminate energy waste by minimizing the electric lighting when there is no one present or when there is an alternative light source available. Galasiu et al. (2007) carried out a year-long field study of a large office in Canada operating with time scheduling, occupancy sensors, daylight harvesting and individual dimming. The lighting was provided by direct/indirect luminaires mounted centrally over each cubicle and providing 450 lx on the work surface at full light output. They found that with the automatic controls, the lighting installation used approximately 45% of the energy that it would have used if kept at full light output throughout the working day. They also state that surveys show high occupant satisfaction and ascribe this to the option of individual dimming, although the use of this was rare after the initial setting had been made.

The success of automatic electric lighting controls in this case should not be taken to mean that they can be applied without care. Rather, care is required because they are automatic and therefore do not take into account the vagaries of human nature and office life. In offices, people expect to be provided with the environmental conditions that they need in order to do their work, and appropriate lighting is one of the most important of those conditions. Any automatic electric lighting control system that fails to provide the expected conditions when called for, or which is distracting because of the nature and frequency of its operation, stands the risk of producing complaints or being sabotaged. Occupancy sensors that are insufficiently sensitive to movement so that they repeatedly switch the electric lighting off when there are people present in the space are not likely to be operating for long. To avoid such a situation, it is necessary to understand the characteristics of the occupancy sensor, to place it in an appropriate location and to commission it so that it has appropriate sensitivity and delay times. Also, as a general principle, all automatic electric lighting control systems should be equipped with a manual override to allow the occupants of the space to take control of the lighting when necessary. It is also a good idea to explain the purpose of the automatic control system. Maniccia et al. (1999) found that the reasons why people adjusted the illuminance in their offices were primarily to do with the work being performed, the need to compensate for daylight and to create an appropriate atmosphere for work. Saving energy was not a consideration. This might be changed by propaganda in favour of energy saving but until it is, and given that the objective of most automatic lighting control systems is to save energy, there is a need to explain why the controls are operating. This is particularly so when the operation occurs while people are present and particularly if the operation makes the visual conditions less satisfactory. An application where this is likely is that of load shedding (see Section 16.6). Load shedding reduces the power demand of the electric lighting so as to reduce the maximum demand of the building on the electricity supply. In doing so, it will reduce the illuminance in some areas. If this is understood by the occupants to be for the general good and as being something necessary to preserve the electricity supply in the community, then it might be accepted, but if it is seen as the company degrading working conditions to make more money to pay for the CEO's stock options, it is likely to be resisted.

7.6 SUMMARY

Office lighting today is more complex than it used to be because of the arrival of electronic displays. Prior to the arrival of these displays, lighting designers concentrated on lighting the desk because that was where the paperwork was done. Today, any lighting installation designed for an office has to be satisfactory for materials that are self-luminous, that is, display screens, and seen by reflected light, that is, paper, and for lines of sight that can be in many different directions. This chapter is devoted to the lighting of offices and is organized around the choices the lighting designer has to make, namely, the illuminance to be provided, the light source to be used, the type of luminaire and its layout and the nature of any lighting controls.

The illuminance on the working plane is a major determinant of satisfaction with the lighting in an office. There is support from a number of sources for the current average illuminance recommendation for offices in North America and Europe of about 300–500 lx on the task. However, it is important to note that simply providing such an illuminance is not enough to guarantee comfortable office lighting. It is also necessary to consider all the aspects of lighting conditions that cause discomfort and that are discussed in Chapter 5.

The first major decision to be made on the light source to be used for office lighting is the balance between daylighting and electric lighting. Daylight always deserves consideration because people like it, as long as it does not cause them thermal or visual discomfort. People like it because, if carefully designed, daylighting fully reveals both the task and the space and provides environmental stimulation by meaningful variation of lighting conditions. By comparison, electric lighting installations usually provide good visibility for the task but rarely provide any environmental stimulation. Electric lighting installations are, in a sense, always playing catch-up to daylighting.

However, electric lighting is always necessary because daylight fails reliably every day. But what spectrum should that electric light source have? The answer to this question depends on what the tasks are. The most universal answer is a light source with a high CIE general CRI (CRI > 80). Such a lamp ensures that tasks that require fine colour discrimination, or tasks where the colour differences are important or tasks where the accurate naming of colours is important can all be done easily. Where only achromatic tasks are involved, then there is little reason to choose any specific spectrum other than by individual preference. There is evidence that a light source with a blue-enriched spectrum can enhance the performance of an achromatic task when the task is close to threshold, due to the spectrum-induced decrease in pupil size, but the effect disappears in suprathreshold conditions. As for the preferred light spectra for offices, the indications are that provided the CRI is high enough (>65) and the correlated colour temperature lies in the range 3000–5000 K, lamp colour properties are a minor factor in determining the satisfaction felt with the lighting of an office. The illuminance provided is much more important. This conclusion should not be taken to mean that light source colour never matters. If the light source colour moves too far from what peoples' expectations are, it is likely that complaints will be heard.

The distribution of light has an influence on the perception of the office. One of the major differences in perception is whether the office is perceived to be primarily lit by daylight or by electric light. As a rule of thumb, any office where the average daylight factor is more than 5% will be perceived as daylit. Conversely, any space where the average daylight factor is significantly less than 2% will be perceived as electrically lit, even in daytime. Daylight can be delivered into an office through conventional windows, clerestory windows or skylights and, over greater distances, by various light guidance systems. By far the most common is the conventional window. The important aspects of windows as far as people are concerned are their size, shape, spectral transmittance and solar shielding. All these aspects are subject to limits, and all should be considered when designing windows.

As for electric lighting systems, the most common arrangement in offices is a regular array of either direct, indirect or direct/indirect luminaires, with or without some form of local task lighting. Of these, there is a clear preference for direct/indirect lighting, probably because such lighting provides direct illumination of both the task and the space and softens any shadows and veiling reflections. However, there is also little evidence for the proposition that light distributions that do not affect task visibility or cause visual discomfort but do change the appearance of the space affect task performance.

The introduction of large numbers of computers into offices led to the design of direct lighting luminaires with restricted luminances above certain angles. These luminaires were designed to minimize the number and magnitude of reflected images seen in the displays standing on desks. The unthinking use of these luminaires created offices that were seen as gloomy and cave-like. Fortunately, there is less and less need for such luminaires. Modern display technology is becoming much less sensitive to the ambient lighting conditions. This is particularly so when the display has a high-luminance background and the screen on which the display is presented has low diffuse and specular reflectances.

As for controls, windows where a direct view of the sun is possible should always be fitted with blinds of some sort. Blinds are used to optimize the performance of a window and are valued by people sitting close to windows as much as the window itself. Most window blind systems are manually adjusted, but automatic systems are available. With automatic blind systems, people are much less accepting of blinds being lowered unnecessarily than blinds being raised. Electric lighting controls can also be automatic or manual. Automatic controls require minimal human intervention, once they have been commissioned. Manual controls require human intervention. How frequently manual controls are used will depend on whether the lighting being controlled is seen as public or private. Public lighting is lighting serving several people, and altering the lighting will affect all of them. Private lighting is lighting serving only one person or a group of people where one person is clearly in charge. Manual lighting controls will be used more frequently in private than in public lighting situations. The other factor determining the probability of use of manual controls is their ease of use. To ensure manual lighting controls will be used, keep them simple and located where the person using the controls can see what effect they have.

There are three common forms of automatic electric lighting controls: time switches, photosensor dimming and occupancy sensors. All three forms have the potential to eliminate energy waste by minimizing the use of electric lighting. Electric lighting can also be used as an acceptable means of load shedding provided the reduction in illuminance is done slowly and smoothly. The problem with all automatic control systems is that they do not take into account the vagaries of human nature and office life. Automatic lighting control systems should be like the perfect butler; they should perform without being noticed and only when required. The closer any specific system gets to this ideal, the more likely it is to be acceptable to the occupants of the office.

8 Lighting for Industry

8.1 INTRODUCTION

The study of lighting for industry is the Cinderella of lighting research. Compared to the effort that has been put into studying lighting for offices, lighting for industry had been sadly neglected. The reason for this neglect is not the lack of importance of lighting for industry, but rather the difficulty in generalizing any conclusions. The nature of the work done in an office is similar in all offices, so any conclusions reached from research are relevant to all offices. The same cannot be said for industry. Study of the optimum lighting conditions for any given industrial activity is likely to be specific to that activity. This makes it difficult to justify research for industrial activities unless there is a specific problem to be solved.

This chapter will review the aspects of lighting that need to be considered for all industrial activities, although whether they are important for a specific industry will depend on the situation in that industry. Recommendations for the lighting of a wide range of industries are given in national standards (BSI, 2007a, 2011a) and in guidance documents published by professional bodies (IESNA, 2011a; SLL, 2012b).

8.2 PROBLEMS FACING LIGHTING IN INDUSTRY

The basic problem facing anyone designing lighting for industry is the wide variability in the amount and nature of visual information required to undertake work in different industries. Some industrial work requires the extraction of a lot of visual information, typically the detection and identification of detail, shape and surface finish. Other types of industrial work require accurate eye–hand coordination and the judgement of colour. Yet other types of industrial work can be done with very little visual information at all. The materials from which visual information has to be extracted can be two dimensional or three dimensional in form, matte or specular in reflection or some combination of the two, and the information can occur on many different planes, implying many different directions of view. Further, the material from which the information has to be extracted can be stationary or moving.

None of these requirements pose insuperable problems, given that the lighting designer has a clear idea of the visual information needed and the nature and location of the material from which the visual information has to be extracted. However, the physical situation within which the work takes place may set constraints on the lighting equipment that can be used. A common constraint is the extent of obstruction. Many factories have overhead conveyors or cranes that obstruct light from high-mounted luminaires. In some factories, the machinery is so large that it obstructs the lighting of the workstations in and around it. Even in small-scale assembly operations, the ability to see inside a box may be limited by shadows cast by the worker. Other situations where lighting equipment with specific characteristics is required are those where there is an explosive, flammable or corrosive atmosphere. Another factor to be considered is the extent to which the atmosphere is clean or dirty. Clean rooms require great care in the delivery of light, so much so that sometimes a light pipe system is used so that the light source can be kept outside the room. As for dirty environments, such as a foundry, the ability of the lighting to deliver the specified lighting conditions will be limited to a short period unless care is taken in the selection, positioning and maintenance of luminaires. There is lighting equipment available to deal with all of these conditions, but the lighting designer has to be aware of the need.

The fact that different levels of necessary visual information occur at different locations in different environmental conditions in different industries implies that the design of industrial lighting is inevitably a matter of tailoring the lighting to the situation. There is no one size fits all solution to industrial lighting. Having said that, it is only fair to point out that there is a limit to how closely the lighting can be tailored. This limit is set by the fact that many different tasks are likely to occur on the same industrial site, within the same building, on the same production line and, certainly, within the area lit by one general lighting installation. The usual solution to this problem is to provide general lighting of the whole area appropriate for most tasks; localized lighting where work is concentrated, for example, on an assembly line; and task lighting where fine detail needs to be seen, for example, on a lathe in a machine shop, or where obstruction reduces the visibility of the task, for example, on the workpiece of a hydraulic press, or where there is an obvious hazard, for example, on the feed to a circular saw. The only place where this general/localized/task lighting approach is impossible is where the scale of the equipment is so large that both the people and the lighting work within the equipment, for example, a chemical plant. For such applications, lighting equipment is integrated into the plant.

8.3 GENERAL LIGHTING

Despite the variability faced by the designer of industrial lighting, the objectives of the lighting are the same everywhere. They are

- To facilitate quick and accurate work
- To contribute to the safety of those doing the work
- To create a comfortable visual environment

The principles of how to use lighting to enhance visual work have been set out in Chapter 4. From the discussion there, it should be clear that the factors that determine the level of visual performance are the visual size, luminance contrast and colour difference of the visual information that has to be extracted and the retinal image quality and the operating state of the visual system. The visual size, luminance contrast and colour difference are determined by the task and its interaction with the lighting. The retinal image quality is determined by the characteristics of the worker's optical system, and the operating state of the visual system is determined by the adaptation luminance and hence the effect of the illuminance provided by the lighting and the reflectance properties of the surfaces illuminated. The amount of light provided, that is, the illuminance on the working plane, is usually determined by the inherent size of detail of the task and its luminance contrast. The smaller is the size and the lower is the inherent luminance contrast, the higher is the illuminance required. This trend is evident from a cursory inspection of any of the illuminance recommendations for industrial lighting (BSI, 2007a, 2011a; IESNA, 2011a; SLL, 2012b). Of course, the working plane may not be horizontal and there may be more than a single working plane. For example, in a warehouse, some areas will be devoted to unpacking and repacking pallets of goods. In these areas, both horizontal and vertical planes may contain the necessary visual information, but in the storage aisles, the primary working plane will be vertical, with the horizontal plane containing little visual information (Figure 8.1).

The locations of the working planes are important in determining the placing and desirable luminous intensity distribution of the luminaires used in the lighting installation. Carlton (1982) argued that the emphasis given to the illuminance on a horizontal plane by the desire to meet illuminance recommendations at minimum cost led to the development and use of industrial luminaires that were apparently energy efficient but in fact were unsuitable for many industrial situations, where the illuminances on vertical planes were important. This problem is not unknown today.

There can be no doubt that knowledge of where the light is needed is essential to the successful design of industrial lighting, but delivering the recommended illuminance in the right place is not enough to guarantee success. The directions from which the light comes are also important, for two reasons. The first is the degree of obstruction. Obstructions cast shadows. The densest shadows are formed when all the light reaching a point comes from one direction and the bounding surfaces are of low reflectance. Therefore, to minimize shadows, it is desirable to have light incident on a point from many different directions. This ideal can be approached by using a larger number of smaller wattage light sources rather than a smaller number of larger

FIGURE 8.1 In industry, it is common for the necessary visual information to be located on several different planes.

FIGURE 8.2 A small workshop with high-reflectance walls and lit by a regular array of luminaires with a wide luminous intensity distribution. The result is a shadow-free environment.

wattage light sources, by using luminaires with a widespread luminous intensity distribution and by having high-reflectance surfaces in the space. Figure 8.2 shows a small workshop where shadows have been minimized by this approach. At the very least, a proportion of the light emitted by luminaires should be emitted upwards to be reflected from a high-reflectance ceiling or roof. The more obstructed is the space, the more valuable this approach is. It should be noted that the obstruction might not always be obvious. A study in a letter-sorting office in Sweden, where the letter sorting was almost entirely automatic with very limited human involvement, hardly seems a good candidate for determining the benefits of different types of industrial lighting. However, it was found that a lighting installation based around a continuous light pipe was preferred over an array of individual luminaires partly because the widespread light distribution produced by the light pipe made it easier to see inside the sorting machines to carry out maintenance (Figure 8.3) (Boyce and Eklund, 1997).

The other reason why the distribution of light is important is the occurrence of veiling reflections. What these are and how they may change the luminance contrast of a task are fully discussed in Section 5.4.3, but basically, veiling reflections are images of high-luminance objects, such as a luminaire or a window, superimposed over the task. For tasks containing a specularly reflecting element, veiling reflections usually decrease task luminance contrast, in which case the visual performance of the task may deteriorate, but this is not the only situation where veiling reflections can make work more difficult. Today, many manufacturing operations are computer controlled through electronic displays. Veiling reflections occurring on the front of the display can make reading the display itself difficult. Methods of limiting veiling reflection in displays are discussed in Section 7.4.2.3. Veiling reflections may also be used to reveal the nature of a surface, in which case they are called highlights, and can be beneficial for the performance of some tasks. Whether veiling reflections are

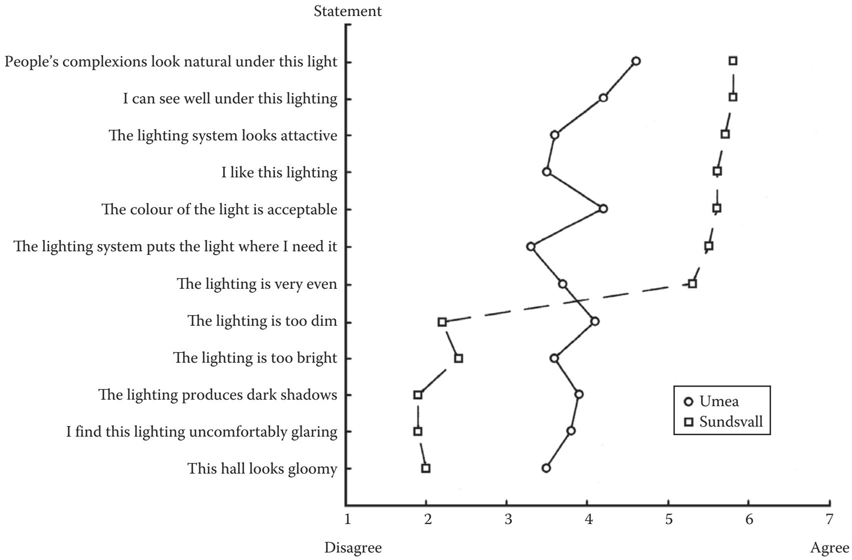


FIGURE 8.3 Mean ratings of agreement with a series of statements about the general lighting of two postal sorting offices in Sweden, both of which use the same automated sorting machinery. The sorting office in Umea is lit by a regular array of specular louvre luminaires containing fluorescent lamps. The sorting office at Sundsvall is lit from a number of rows of continuous light pipe, with the light provided by sulphur lamps. (After Boyce, P.R. and Eklund, N.H., *Evaluations of Four Solar 1000 Sulfur Lamp Installations*, Lighting Research Center, Troy, NY, 1997.)

beneficial or not will depend on the work being done. If they are beneficial, then they are more easily provided by a local lighting installation mounted close to the task. It is generally unwise to try to provide veiling reflections from general lighting. The approach used to minimize shadows, that is, to use luminaires with a widespread luminous intensity distribution and an interior with high-reflectance surfaces, also works to minimize veiling reflections.

The other factor that the designer of the general lighting needs to consider is the spectrum of the light used. Where colour is of no importance, many different light sources have been used in industry. Some, such as the HPS lamp, have poor colour rendering and a distinctly non-white colour appearance (see Section 1.7.3). Where colour is used to convey meaning, for example, in electrical wiring; or where colour is an important determinant of value, for example, when grading diamonds; or where matching colours is an important element of quality, for example, fine colour printing, care should be taken with the selection of the light source. Collins and Worthey (1985) have demonstrated the consequences of choosing an inadequate spectrum for lighting in a study of lighting for meat and poultry inspection. They found that when working under HPS lighting, the inspectors were more likely to pass diseased meat and poultry than when working under fluorescent or incandescent lighting. In general, for the coarse discrimination of colours, a light source with a Commission Internationale de l'Eclairage general colour rendering Index (CRI) of 60 or higher is all that is required. Where finer colour judgments, such as discriminating electrical colour codes, a light source with a CRI of 80 or greater is recommended (SLL, 2012b). Where the judgment of colour has a major impact on the value and/or quality of a product, then specific lighting recommendations are made, and the lighting is provided in either special rooms or booths. For example, for grading cotton, an illuminance in the range 600–800 lx, provided by a light source with a spectral power distribution simulating daylight, is recommended (ASTM, 1996a). For the examination of colours of opaque objects, national standards have been developed (ASTM, 1996b).

All of the above details has been concerned with the objective of facilitating quick and accurate work, and it has been implicit that the only way to do this is to improve the lighting. However, it should always be remembered that it might also be possible to make the task easier by changing the task characteristics. For example, Ruth et al. (1979) carried out a thorough analysis of the work processes and lighting conditions in foundries in Sweden. They found that workers doing manual casting worked in very poor visual conditions because of the low illuminances in the work area, the low contrast between the molten metal and the mould and the use of low transmittance eye protectors. They certainly suggest increasing the illuminance as a means of improving working conditions, but they also suggest redesigning the mould so as to increase the contrast between the part of the mould into which the molten metal is poured and the rest of the mould. It is always worth considering if the task can be changed to make it visually easier before undertaking a major lighting change.

Another objective of industrial lighting is to contribute to the safety of the workers. Consideration of the impact of lighting on safety is necessary in all lighting applications, but it is particularly important in industrial situations. This is because of the complex layout of many plants, the hazards associated with some manufacturing processes and the dangers from moving equipment. Minimum illuminances are recommended for safety whenever the space is occupied, ranging from 4 to 75 lx depending on the nature of the hazard, the level of circulation activity and the surface reflectances (IESNA, 2011a). But illuminance alone is not enough. Hazardous situations can arise whenever seeing is made difficult by disability glare, strong shadows and poor uniformity of illuminance. Care should be taken to avoid these conditions.

Safety will also be enhanced by marking hazards with the appropriate colours (ANSI, 1998), but this will be of little use if the light sources used do not allow the safety colours to be correctly named. Jerome (1977) examined people's ability to name safety colours at an illuminance of 5 lx, close to the lowest illuminance recommended for safety lighting. He showed that light sources with low CRIs, such as HPS discharge lamps, made it difficult to correctly identify some of the safety colours. How much these findings are due to the low illuminance and how much to the light spectra of the different light sources remains to be determined. What is known is that the ability to correctly name colours with poor colour rendering lamps improves as the illuminance increases (Saalfield, 1995) and that accurate colour naming is possible with light spectra covering a wide range of colour rendering properties, given an illuminance of more than 100 lx (Boynton, 1987; Boynton and Purl, 1989).

One aspect of safety that needs to be considered where there is rotating or reciprocating machinery is the possibility of a stroboscopic effect. A stroboscopic effect is evident when oscillations in the illumination of a moving object cause that object to appear to move at a different speed from the speed it is actually moving or even to appear to be stationary. All light sources operating from an AC electrical supply produce oscillations in light output, oscillations that may not be directly visible. Whether these oscillations are enough to produce a stroboscopic effect will depend on the frequency and amplitude of the oscillation. The closer the fundamental frequency of light oscillation is to the frequency of rotation and the larger the amplitude of light oscillation, the more likely a stroboscopic effect is to occur. The probability of a stroboscopic effect occurring can be reduced by using electronic control gear for discharge lamps because such control gear significantly increases the frequency and reduces the amplitude of the light oscillation. As for solid-state lighting, the probability of a stroboscopic effect occurring depends on the characteristics of the driver and the presence or absence of a phosphor. When the driver delivers perfect DC to the light-emitting diode (LED), a stroboscopic effect is impossible because there will be no light oscillation. However, the rectification circuits of drivers operating on an AC supply vary considerably in their ability to achieve stable DC, and when they fail to do so, the very fast response time of an LED can produce considerable light oscillation, particularly if there is no phosphor involved in light production. To further complicate this issue, it is common to dim LEDs using pulse-width modulation, a process that involves chopping the waveform. Depending on the frequency of chopping, there is an increased probability of a stroboscopic effect occurring when an LED lighting system is dimmed.

Another approach to reducing the likelihood of a stroboscopic effect occurring is to mix light from light sources operating from different phases of the electricity supply before it reaches the relevant machinery. Such mixing increases the frequency and reduces the amplitude of the light oscillation. It is also possible to reduce the probability of a stroboscopic effect by supplementing the general lighting of machinery with task lighting using a light source with inherently small oscillation in light output, such as some form of incandescent lamp.

The final objective of industrial lighting is to create a comfortable visual environment. This objective is not always given the attention it deserves. This will be evident to anyone familiar with industrial lighting, the design of which is too frequently dominated by a desire to maximize lighting system efficiency. This desire is often consummated through a lighting installation, which uses the smallest number of luminaires, containing the highest wattage light source, positioned at the widest allowed spacing, and directing most of their light downwards to an assumed horizontal working plane. This is a recipe for deep shadows, strong veiling reflections and possibly discomfort glare, as well as inadequate illumination on vertical planes (Carlton, 1982). That these disadvantages are recognized is demonstrated by the preference of industrial workers for luminaires with a significant proportion of upward light over luminaires with no or little upward light (Subisak and Bernecker, 1993). Such upward light will be reflected from the ceiling or roof of an industrial building. Provided that the reflectance of the ceiling or roof is high, the diffusely reflected light will weaken both shadows and veiling reflections, diminish any discomfort glare and provide some light on any vertical working surfaces.

The lower priority given to eliminating visual discomfort in industrial lighting is also evident in commonly used lighting recommendations. For example, the criteria for discomfort glare are usually much less stringent for industrial applications than for offices (SLL, 2012b). Further, a wider range of light sources is considered acceptable for industrial use than for offices, including some discharge light sources that have poor colour rendering properties but high luminous efficacies. There is no logical reason why this should occur. People who work in industry have the same visual system as those who work in offices. Rather, it is a matter of expectations. Many aspects of the physical environment are less comfortable in industry than in offices, and lighting is just one of them. The quality of industrial lighting would undoubtedly be better if all the aspects of visual discomfort discussed in Chapter 5 were considered by those designing industrial lighting.

8.4 LOCALIZED AND TASK LIGHTING

Localized and task lighting can take many different forms and serve many different purposes. Probably the most common forms are the fixed luminaire that provides additional illuminance in a localized work area and the adjustable task luminaire that allows the worker to have some control over the lighting of the task. Fixed localized lighting is common where the work area is in shadow. Adjustable task lighting is common where the tasks to be done are much more visually difficult than average and the ability to manipulate the light distribution on the task is of value. For large-scale manufacture, localized lighting can be moveable, consisting of luminaires mounted on a wheeled frame, so that lighting can be moved into position when work demands it. Fixed localized lighting rarely does more than provide a higher illuminance, but this can be effective in raising productivity. Juslen et al. (2005, 2007a) carried out a prolonged field study in a windowless luminaire assembly area in Finland using fixed but dimmable localized lighting that could raise the illuminance on the individual assembly areas from an average of 270–3300 lx. The average illuminance chosen by nine people who had worked in the assembly areas for at least 2 months was 1405 lx. This localized lighting was claimed to be responsible for an increase in productivity of 4.5%, although whether this occurred because of changes in visual performance, alertness or mood or some combination of them could not be determined. It should also be appreciated that such an effect may be specific to the task. A field study in an electronics factory in the Netherlands showed that increasing the illuminance on the task from 800 to 1200 lx during the night shortened the production time for five products but increased it for two (Juslen and Fassian, 2005). Regardless of whether there is a performance benefit, localized or task lighting under individual control is usually appreciated even if it is rarely used (Juslen and Tenner, 2007).

8.5 VISUAL INSPECTION

One type of local lighting that can take many different forms, each form being designed for a particular function, is lighting for visual inspection. Visual inspection work involves two separate but successive components. The first is the search for and identification of any defects. The second is deciding on what to do about the identified defects. Lighting can only directly affect the first component.

Studies of eye movements made while searching for defects in products have revealed a common pattern of fixation and saccade. The observer searches through a series of fixation pauses with rapid saccadic eye movements between them. Figure 8.4

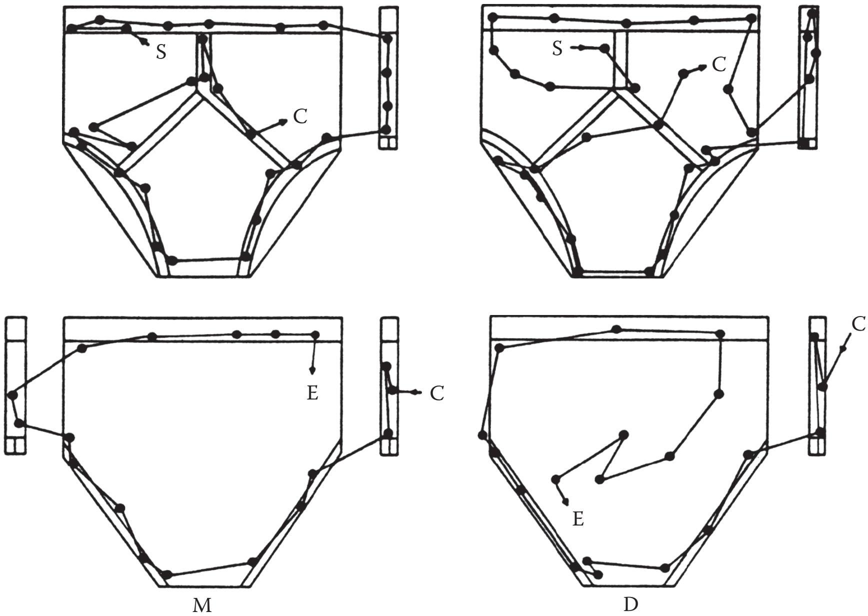


FIGURE 8.4 The pattern of fixations made by two inspectors examining men's briefs held on a frame. S, start of scan path; C, end of scan of front and one side, rotation of frame and continuation of scan across back and sides; E, end of scan. Inspector M examines only the seams while inspector D examines the fabric as well. (After Megaw, E.D. and Richardson, J., *Appl. Ergon.*, 10, 145, 1979.)

shows such an eye movement pattern made by an inspector examining men's briefs held on a frame. Observations of this sort illustrate that the search pattern made by experienced inspectors is often systematic rather than random, the search pattern being based on the inspector's expectations about where the defects are likely to occur (Megaw and Richardson, 1979). The fixation and saccade pattern of visual search implies that the defect, or something that may be a defect, is likely to be first detected off-axis, that is, in the peripheral visual field, and subsequently confirmed by bringing the fovea to bear on it through a saccadic eye movement. Therefore, the essential requirements for rapid visual search are off-axis detection of a defect, preceded by a clear definition of what constitutes a defect. Lighting cannot provide a clear definition of a defect for the inspector, although it can sometimes be designed to reveal the visual characteristics that define a defect, once that definition is available. What lighting can always be designed to do is to enhance the probability of off-axis detection of a defect. For a uniform field, where any departure from uniformity is a defect, the probability of off-axis detection can be related to the visibility of the defect. Figure 8.5 shows mean search time plotted against defect size for the inspection of a sheet of glass for a single defect (Drury, 1975). It is clear that as the defect size increases, which will make it more visible, the search time decreases.

The concept used to model the effect of lighting conditions on search time is the visual detection lobe, that is, a surface centred on the fovea that defines the probability of detecting the defect at different deviations from the fovea within a single fixation

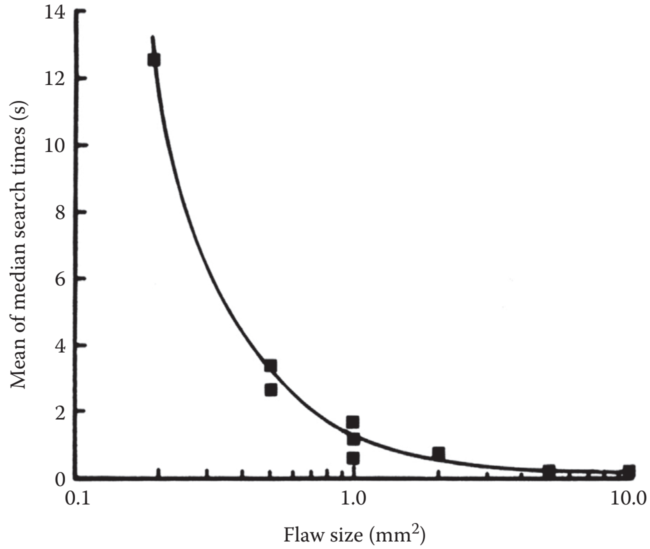


FIGURE 8.5 Mean of the median search times for detecting a single flaw in a sheet of glass, plotted against the flaw size. (After Drury, C.G., *Human. Factors*, 17, 257, 1975.)

pause (Bloomfield, 1975a). Figure 8.6 shows some probability data for detecting targets of different sizes and luminance contrasts. From such results, it is possible to calculate a visual detection lobe for each target by assuming radial symmetry about the visual axis. As would be expected, such visual detection lobes have a maximum at the fovea – the probability of detecting the defect decreasing as the defect is located further off-axis. Clearly, different defects will have different visual detection lobes. A large-area, high-contrast hole in some sheet material will have a large visual detection lobe, while a small-size, low-contrast hole will have a small lobe. The size of the visual detection lobe matters because, provided the distance between fixation points is related

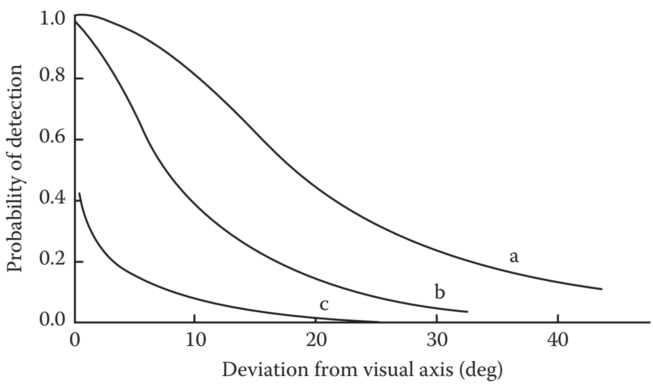


FIGURE 8.6 The probability of detection of targets of (a) contrast = 0.058, size = 19 min arc; (b) contrast = 0.08, size = 10 min arc; (c) contrast = 0.044, size = 10 min arc, within a single fixation pause, plotted against deviation from the visual axis. Each curve can be used to form a visual detection lobe for each target by assuming radial symmetry about the visual axis.

to it and the total search area is fixed, the total time taken to cover the search area is inversely proportional to the size of the visual detection lobe. Visual detection lobes can be measured directly by psychophysical procedures or estimated from threshold performance data available for peripheral vision (Boff and Lincoln, 1988). Howarth and Bloomfield (1969) have suggested a simple equation, based on a random search pattern, which can be used to predict search times. The basic form of the equation is

$$t_m = t_f \times \left(\frac{A}{a}\right)$$

where

t_m is the mean search time (s)
t_f is the mean fixation time (s)
A is the total search area (m^2)
a is the area around the line of sight within which the target can be detected in a single fixation, that is, the visual detection lobe for the fixation time (m^2)

For the inspection of a given article, the total search area is likely to be fixed, and the mean fixation time is likely to be reasonably constant, so the mean search time becomes proportional to the reciprocal of the size of the visual detection lobe. This implies that for searching uniform, empty fields, it is the visibility of the defect off-axis that determines the search time. However, for many inspection tasks, the defect appears not in a uniform, empty field but in a cluttered field, that is, one in which many different items are present. In this situation, the visibility of the defect alone is not enough to predict the search time. The other factor that must be considered is the conspicuity of the defect, that is, how easy it is to distinguish the defect from the other items in the search area. High visibility is not enough to guarantee high conspicuity. As an example of this, consider searching for a person in a crowd. All the people are equally visible, but if the person being sought is wearing a red hat and the rest of the crowd is hatless, then the person being sought is conspicuous as well. For high conspicuity, the defect should differ from the other items in the field on as many dimensions as possible. Figure 8.7 shows the mean search times for two observers searching for rectangular or square targets among an array of square non-targets, plotted against an index of discriminability. Discriminability is given by the square of the difference in the square roots of the areas of the targets and non-targets (Bloomfield, 1975b). This result, and others like it, suggest that it should be possible to estimate an effective visual detection lobe where the lobe is determined not only by the target but also by the other items among which it is seen, that is, not only by the visibility of the defect but also by its conspicuity. Engel (1971, 1977) has shown how such an effective visual detection lobe can be measured and has demonstrated that it is related to the probability of finding a target within a fixed time.

It is important to appreciate that there are many different dimensions besides size on which the target can differ from the items around it. As discussed in Section 7.3.2.1, Williams (1966) studied search times for finding a specific item in a display of 100 items that could vary in size, shape, colour and the two-digit number contained. The inspector was asked to locate a particular item, where either the number alone was specified or the number and various combinations of the size, colour and shape of the item on

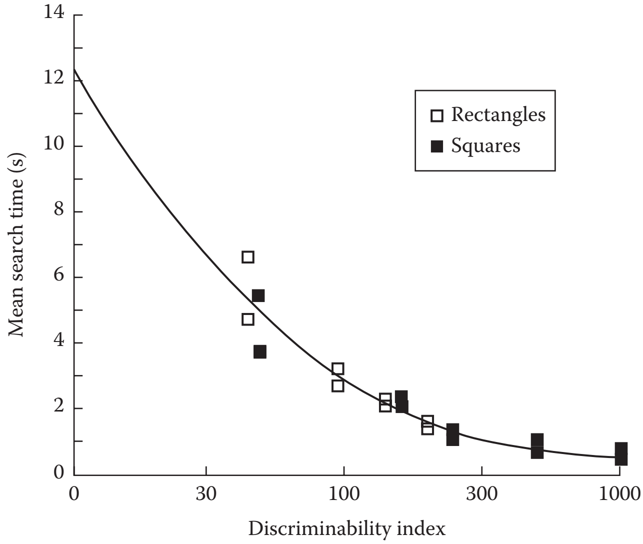


FIGURE 8.7 Mean search times for two observers searching for rectangular or square targets among an array of square non-targets, plotted against an index of discriminability. The discriminability index is given by $(A_1^{0.5} - A_2^{0.5})^2$, where A_1 and A_2 are the areas of the targets and non-targets, respectively. (After Bloomfield, J.R., Studies in visual search, in C.G. Drury and J.G. Fox (eds.), *Human Reliability in Quality Control*, Taylor & Francis, London, U.K., 1975b.)

which the number was printed were specified. The results showed that some aspects of the specification were more important than others. Specifically, whenever the colour of the item was specified, short mean search times were achieved, but specifying the shape showed little reduction in mean search time from what it was when the number alone was specified (see Table 7.1). The explanation for these results is that the differences in colour give a much larger effective visual detection lobe than do differences in shape. This explanation is supported by measurements of the eye movement patterns made during the search. Whenever the colour was specified, fixations were made predominantly on items of that colour. When the shape was specified, there was little change in the eye movement patterns from when the number alone was given. One possible explanation for this difference in pattern of eye movements is that the items of a specified colour have a large enough visual detection lobe that fixation on one item with the specified colour allows off-axis detection of an adjacent item of the same colour. Another possibility is that colour is extracted from the retinal image at an earlier stage of neural processing than the spatial relationships required to identify a shape (Enns and Rensink, 1990).

Given that the efficiency of visual search is determined by the actual or effective visual detection lobe, the role of lighting conditions in visual search is to increase the size of the visual detection lobe. Many of the lighting techniques used for visual inspection are aimed at increasing either the visual size or luminance contrast of the defect and either by casting shadows (Figure 8.8) or by using specular reflections (Figure 8.9). Faulkner and Murphy (1973) list 17 different methods of lighting for inspection. Their methods can be classified into three types: those that rely on the distribution of light, as shown in Figures 8.8 and 8.9; those that

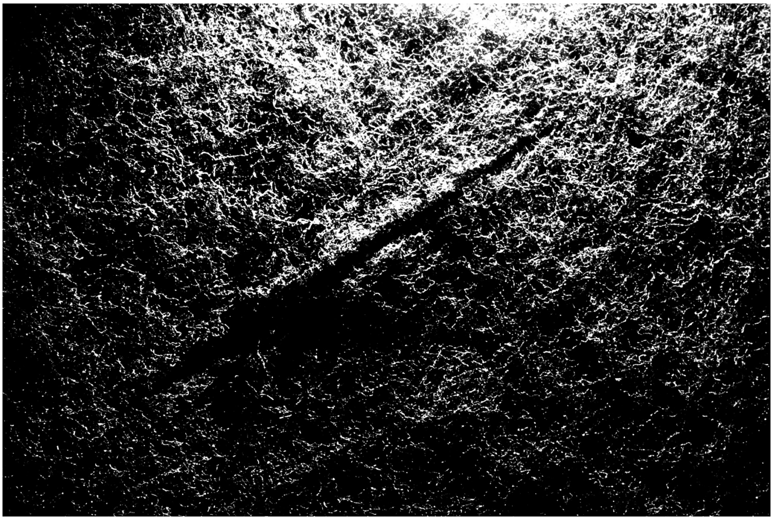


FIGURE 8.8 A cut in textured material lit by directional lighting delivered at a glancing angle to the surface of the material. The cut is visible under the directional lighting because of the high-luminance contrast. The high-luminance contrast occurs because of the highlights on the sides of the cut and the deep shadow in the cut.

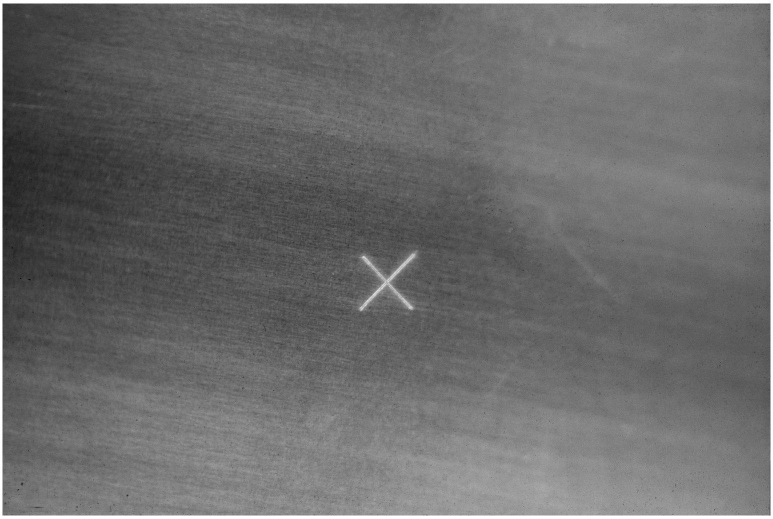


FIGURE 8.9 A specular aluminium surface with a cross scribed into it, lit by directional lighting from above and behind the camera. The scribed cross is easily seen because the scribed marks cut into the surface and thereby alter the reflection characteristics of the surface. The result is a high-luminance reflection towards the camera for the cut and a high-luminance reflection away from the camera for the undamaged surface.

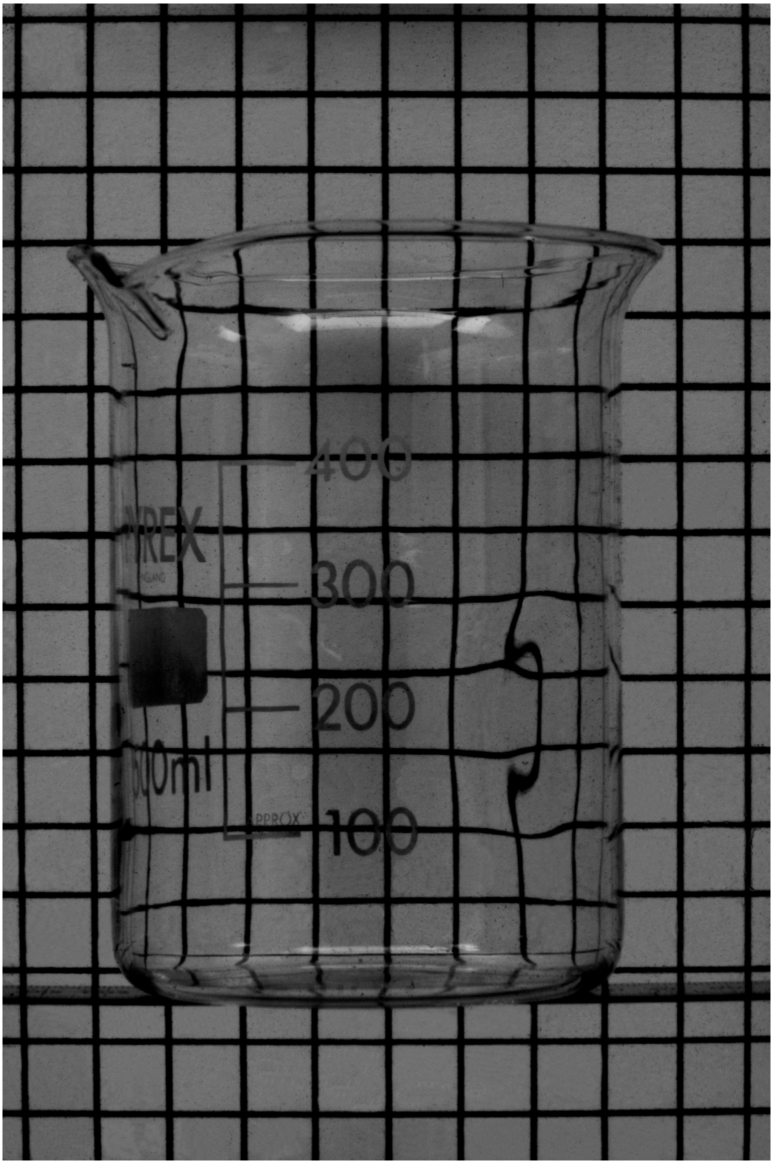


FIGURE 8.10 A distortion in a transparent glass beaker is revealed by the distortion in the grid seen through the beaker.

rely on some special physical property of the light emitted that interacts with the material being inspected, for example, UV radiation for detecting the presence of some types of impurities in a product; and those that call for the projection of a regular image onto or through the material being studied. Figure 8.10 shows this last approach. Any distortion of the grid when it is viewed through the beaker indicates a defect in the glass.

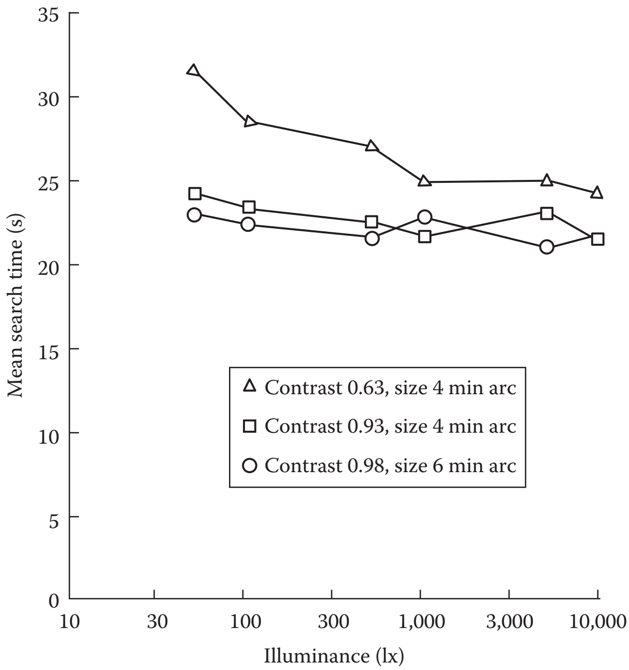


FIGURE 8.11 Mean search times for locating a specified two-digit number from a random array of 100 such numbers, plotted against illuminance, for numbers of three different size and contrast combinations. (After Muck, E. and Bodmann, H.W., *Lichttechnik*, 13, 502, 1961.)

Probably the most widely applicable aspect of lighting, which aids visual inspection, is to increase the illuminance on the search area. Figure 8.11 shows the mean search times for finding a specific two-digit number located among 100 such numbers randomly arranged on table, plotted against the illuminance on the table. Increasing the illuminance leads to shorter search times, particularly for the small-size, lower-contrast target (Muck and Bodmann, 1961).

While illuminance is generally a useful method of reducing search times, it should not be used without thought. If the effect of increasing illuminance is to decrease the luminance contrast or effective visual size of the defects or to produce confusing visual information in the search area, visual inspection performance will be worse with higher illuminances. An early example of this is shown in Figure 8.12, which gives the time taken for the inspection and packing of cartons of 25 shotgun cartridges during the period immediately before and after lighting was switched on in the afternoon of a winter working period (Wyatt and Langdon, 1932). The sudden reduction in the speed of inspection with the onset of lighting from a single incandescent lamp overhead is obvious. The important point to note is that this onset of lighting almost certainly increased the illuminance on the task, but this caused a worsening of performance. The inspectors stated that the electric lighting produced an element of reflected glare from the brass caps of the cartridge cases, and the cases were less uniformly lit. Thus, in this case, the increased illuminance was provided in such a way that the defects became more difficult to see. These results

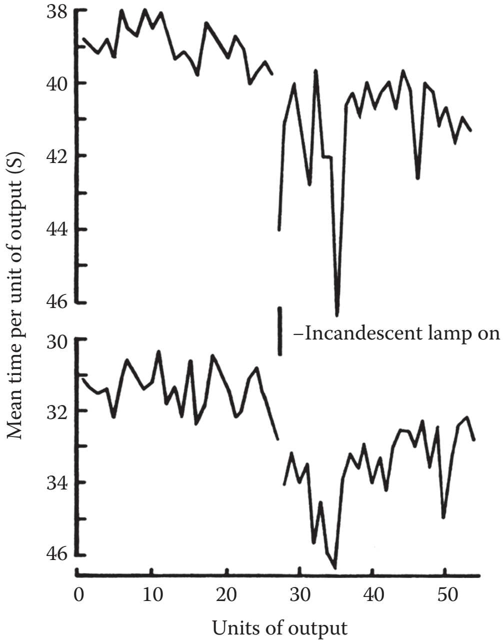


FIGURE 8.12 Mean time taken by two workers to inspect and pack cartons of 25 shotgun cartridges before and after an incandescent lamp was switched on. (After Wyatt, S. and Langdon, J.N., *Inspection Processes in Industry*, Medical Research Council Industrial Health Research Board Report 63, His Majesty's Stationary Office, London, U.K., 1932.)

demonstrate the need to understand the whole impact of a lighting installation on visual search rather than just the illuminance.

Another example of the need to understand the whole impact of a lighting installation that occurs is the inspection of topographic defects in painted automobile body shells (Wiggle et al., 1997). There are many different forms of defect in automobile paint finishes, ranging from unwanted mixing of colours to surface defects, such as runs, sags and orange peel. However, one of the most difficult to see is the presence of dirt particles that fall into the paint before it hardens. These are difficult to be seen in the factory because they are small, they are the same colour as the paint and they are enrobed in the paint and, for the same reason, have no luminance contrast. Yet, such dirt defects are sometimes seen by purchasers in sunlight, and their presence leads to warranty claims against the manufacturer. There is therefore considerable interest in using lighting to make it easier for the inspectors in the paint shop to detect and rectify such dirt defects. To design appropriate lighting, it is first necessary to understand the physics of the situation. A typical painted automobile shell has multiple layers of paint. For the purposes of visibility, it is only the top two layers that matter. These layers are usually a pigmented coat that gives the surface its colour and a clear sealing coat that gives the paint its gloss finish. Light incident on the surface of the paint is partially specularly reflected from the clear-coat layer and partially transmitted through the clear-coat to the pigmented layer, where it is diffusely reflected. This

FIGURE 8.13 A lighting installation designed to make dirt defects in painted automobile body shells easier to detect. (Courtesy of Acuity Brand Lighting Inc., Atlanta, GA.)

structure is the key to designing appropriate lighting. A speck of dirt in the paint provides a local deflection in the paint surface. This deflection will be most evident when the specular reflection from the clear-coat surface is emphasized and the diffuse reflection from the underlying pigmented surface is diminished. This can be achieved by using a series of discrete, high-luminance points or lines to illuminate the painted surface. The areas between each discrete, high-luminance point or line should be of low luminance. Figure 8.13 shows such an installation. When the inspector looks at the vehicle, the effect is to see the specularly reflected image of the installation, but in addition, any deflections in the painted surface close to the image of the light source now have a highlight attached to them, a highlight that itself has a high-luminance contrast and hence is likely to be more easily detected off-axis. Figure 8.14 shows a close-up of the image of a fluorescent tube reflected from a piece of black-painted automobile. The highlight to one side of the reflection of the lamp is caused by a dirt defect. When the dirt defect is beneath the image of the lamp, then the deflection has a much lower luminance than the image. In both situations, the dirt defect has a high-luminance contrast and, hence, is much more likely to be detected off-axis. Obviously, this approach will only work within a short distance of the reflected image of the lamp (Lloyd et al., 1999). To overcome this problem, the usual approach is to space fluorescent luminaires at regular intervals, so the vehicle is seen as being covered with stripes of light (Figure 8.13). The movement of the vehicle through the inspection area ensures that the reflected images sweep over the whole body shell, giving the inspector multiple opportunities to detect the dirt defect.

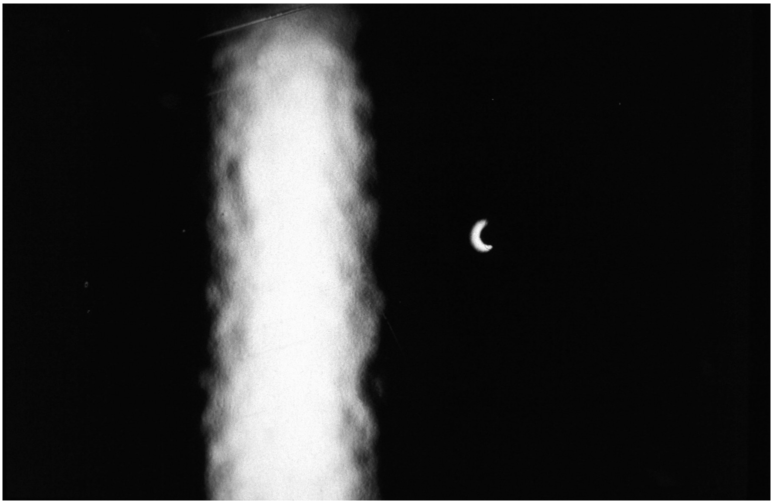


FIGURE 8.14 A close-up photograph of the image of a fluorescent lamp seen by reflection in a painted automobile surface. The large bright stripe is the image of the lamp. The small bright crescent to one side of the image of the lamp is a local highlight produced by light from the lamp striking a small bump in the surface caused by a speck of dirt in the paint.

The problem of how to light a paint inspection area for the automobile industry has been considered in some detail because it demonstrates the sort of process that is necessary to develop a successful solution. Whenever visual inspection lighting is under consideration, it is necessary to have a clear understanding of the physical nature of the defect and how it interacts with light and the constraints imposed by the conditions in which the inspector works. Simply providing more light, without thinking about the consequences for the visibility and conspicuity of the defect, may make visual inspection more difficult. It is also necessary to consider the consequences of providing lighting to make it easier to detect one type of defect for the ability to detect others. The striped image shown in Figure 8.13 is very good for revealing dirt defects, and other defects that cause local deflections in the paint surface, but may make it more difficult to detect fine changes in colour and large-area defects such as swirl marks. Finally, it is necessary to appreciate that visual inspection by humans may not be the only possibility. Automated inspection is possible for many simple, repetitive inspection tasks and is steadily increasing in sophistication (Newman and Jain, 1996; Pham and Alcock, 2002). The main advantage of automated inspection is that the detection criterion is clear and automated inspectors are fast and do not become bored and inattentive.

To summarize, the general problem with identifying the best lighting conditions for visual search is that they are likely to be specific for each situation. It is clear that lighting that increases the effective visual size or luminance contrast or colour difference of the item being sought or that makes the visual system more sensitive to differences in visual size, luminance contrast or colour differences is likely to improve the performance of a visual search task (Kokoschka and Bodmann, 1986). However, the specifics of such lighting depend critically on the area to be searched, what else that area contains and the luminous and colour characteristics of the items in the area, including the defect. The Society of Light and Lighting's Lighting Guide 1 (SLL, 2012b) provides a summary of lighting techniques commonly used for visual inspection.

Finally, it is important to appreciate that the complete visual inspection task involves a lot more than just the ability to see the defect. Inspection is often done at a set speed, which limits the time available for searching, and once the defect has been detected, there comes the decision as to what to do about it, a decision that is influenced by social, organizational and psychological factors. Lighting has a part to play in visual inspection, but it is a limited part. Other factors such as the time allowed to inspect the item and the manner of presentation are also important. Megaw (1979) gives an interesting review of these factors.

8.6 SPECIAL SITUATIONS

There are two features of industrial lighting applications that deserve special consideration from the lighting designer. They are the widespread practice of shift work and the increasing number of self-luminous displays used in industry.

About 15% of the work force in the United States undertakes evening, night or rotating shift work (Bureau of Labor Statistics, 2005). The amount and quality of work done during the night shift is usually worse than is done during a normal working day (Folkard and Tucker, 2003), presumably because the workers have to be attentive and alert while their physiology is telling them to go to sleep. Further, prolonged shift work can have adverse consequences on the workers' health (Arendt, 2010) and may disturb their social life (Walker, 1985). Lighting cannot solve all these problems, but it can, at least in principle, do something about the major complaint of people doing night-shift work, the accumulating feeling of tiredness caused by poor-quality sleep during the day. One possibility is to speed up adaptation to working at night by using an appropriate pattern of light exposure to shift the phase of the human circadian system (see Section 4.4.1), but this is not often used in practice. This is because it requires control over light exposure over the whole 24 h to be effective and takes several days to be completed. These limitations mean it is only worth considering when night-shift work is prolonged.

Unfortunately, one of the most common forms of night-shift work is the rapidly rotating system where only 2 or 3 days are spent on the same shift before moving on to a different shift or to non-working days. People working nights on such a system are almost certainly going to be physiologically maladapted resulting in a lack of alertness and increased confusion when asked to do a cognitively difficult task. These problems can be overcome by relatively brief exposures to bright light at night. For example, Figueiro et al. (2001) have shown how the installation of bright light in a break room leads to a reduction in the number of errors made in calculating the correct dosage of medication for small babies in a neonatal intensive care unit. Also, Lowden et al. (2004) were able to produce an improvement in perceived alertness among workers in a truck production plant by installing a high illuminance in a break room used between 20 and 41 min/shift. Bright light in this study was created using indirect lighting and high-reflectance room surfaces so that an illuminance of 2500 lx was produced at the eye. The probable explanation for these findings is that the pattern of exposure to light partially re-entrains the circadian timing system. Smith et al. (2009) have proposed a compromise procedure to achieve this aim by delaying the onset of melatonin so that the time of maximum sleepiness occurs at 10.00 h. This has the advantage of enhancing alertness during the night shift as well as ensuring afternoon and evening alertness on days off. The procedure involves exposure to 15 min of bright light (4100 lx at the eyes from a 5095 K light source) every hour, for 4 or 5 h starting at about 00:45. In addition, subjects had to wear dark sunglasses when outside during the day and sleep in a dark bedroom for set hours at the end of the shift and on days off. The effects of this procedure were improvements in performance of a battery of tests, better mood and less fatigue for the partially re-entrained group.

Others have examined the effect of an enhanced illuminance provided all the time. Juslen et al. (2007b) introduced localized lighting to provide either 350 or 2000 lx on the packaging lines of a chocolate factory. The people monitoring and repairing the packaging machines were working a rapidly rotating shift system in which they did successive, 2-day morning, evening and night shifts followed by 4 days off. It was found that overall, repair times were 3% shorter with the higher illuminance. While this could be considered to be a useful contribution to productivity, it is worth noting that the pattern of repair times with shift was complex, only some repair types showing a difference between illuminances and then only in the morning and night shifts. The fact that such improvements in repair time only occurred in some shifts suggests that circadian misalignment was involved, but the fact that only some repair types were affected suggests that changes in visual performance were also involved. Such are the difficulties in interpreting even well-conducted field studies.

Another feature of industrial work that is growing rapidly is the use of self-luminous displays as parts of control systems for machines. The impact of lighting conditions on the visibility of such displays deserves careful consideration. Inappropriate lighting can reduce the luminance contrast of all parts of the display and/or produce discomfort by providing high-luminance reflections on the display that are distracting. The lighting conditions necessary to avoid these problems are discussed in Section 7.4.2.3 in the context in offices. The principles discussed there also apply to industrial situations, although it is important to remember that the lines of sight to the displays are likely to be much more variable in industrial situations than in offices.

One application that combines both night-shift work and a large number of displays is the control room. The consequences of errors in control rooms can be large, in societal, environmental and financial terms, for example, the Chernobyl disaster. Therefore, there is every reason to attempt to make the control room a place where the lighting helps rather than hinders the collection of visual information, improves the alertness of workers during the night shift and minimizes stress and fatigue. What needs to be done to ensure good visibility for sources of information is well understood, although not always implemented. The possibility of using lighting to increase alertness during the night shift by the acute suppression of the hormone melatonin is discussed in Section 4.4.1. As for minimizing stress and fatigue, Sato et al. (1989) describe a study of the perceptions of the visual environment in a control room. The visual environment was varied from a standard windowless control room design by changing the lighting system, the illuminance, the presence of a window, the ceiling height, the colour of the floor, the colour of the control panels and the presence or absence of decorative items, such as potted plants. The observers' appraisal of the visual environment was made on two dimensions: spaciousness and friendliness. Table 8.1 shows the effects of changing these various features. Clearly, many different aspects of the visual environment, including the type of lighting, can change the perception of spaciousness and friendliness, for better or worse. Too often, lighting designs for control rooms are dominated by the need for information to be easily seen. While this is undoubtedly important, alone, it is not enough. The lighting design for a control room also needs to consider the possible effect of the lighting on the non-image-forming system and the effects of the visual environment on mood and behaviour if it is to be successful.

TABLE 8.1
Impact of Various Modifications of the Visual Environment of a Control Room on the Perceptions of Spaciousness and Friendliness

New Feature	Change	Spaciousness	Friendliness
Lighting system	Louvres (40%)	–	–
	Louvres (100%)	–	0
	Luminous ceiling	+	–
	Luminous ceiling with recess	0	+
Illuminance	2000 lx non-uniform	+	+
Window	Inside window	+	0
	Outside window	+	+
Ceiling height	3.5 m	+	+
	4.2 m	+	+
Floor colour	Matte N8	–	0
	Matte N6	–	0
	Beige	0	+
Panel colour	Ivory	+	+
Decorative items	Potted plants	0	+ +
	Accessory colours		+

Source: After Sato, M. et al., *Lighting Res. Technol.*, 21, 99, 1989.

Note: The standard lighting was an array of recessed luminaires with 80% reflectance louvres providing 1000 lx. There were no windows. The ceiling height was 2.8 m. The floor colour was gloss N8. The panel colour was green, and there were no decorative items.

+ +, Much improved; +, improved; 0, unchanged; –, worsened.

8.7 SUMMARY

The visual requirements for industrial work can vary greatly. Some industrial work requires the extraction of a lot of visual information, typically involving the detection and identification of fine detail and fine differences in colour. Other types of industrial work require different forms of visual information, for example, shape and texture rather than detail and colour. Yet other types of industrial work can be done with very little visual information at all. The materials from which visual information has to be extracted can be two or three dimensional in form, matte or specular in reflection, located on many different planes and moving or stationary. Further, the nature of the process may impose constraints on the type of lighting that can be used, for example, where obstruction is extensive and where the atmosphere is hazardous, corrosive or just plain dirty. This variability means that good industrial lighting is inevitably tailored to the application.

Despite this variability, the objectives of industrial lighting are the same everywhere. They are to facilitate quick and accurate work, to contribute to the safety of those doing the work and to create a comfortable visual environment. The principles of lighting for quick and accurate work are discussed in Chapter 4. Applying these principles to industry requires an understanding of the information that needs to be obtained to do the work, where it is likely to be found and the constraints imposed by the application. Once this information is collected, the necessary amount, distribution and spectrum of light delivered can be determined.

Minimum illuminances are recommended for safe movement, but illuminance alone is not enough. Care needs to be taken to avoid disability glare and strong shadows. Light sources should also be chosen to make the correct naming of safety colours easy. Where rotating or reciprocating machinery is in use, care should be taken to minimize any stroboscopic effect.

As for comfort, the aspects of lighting that can cause discomfort are discussed in Chapter 5. In principle, the same comfort conditions should be applied to lighting installations wherever they are used. Unfortunately, this is sometimes not the case in industry. Many aspects of the physical environment are less comfortable in industry than in offices, and lighting is often one of them.

Many industrial lighting installations are designed around a general/localized/task lighting approach, the localized lighting being used where activity is intense, for example, on an assembly line, and the task lighting being used where tasks are either critical or more difficult than usual. One form of task lighting that requires special care is lighting for visual inspection. Rapid visual inspection calls for off-axis detection of defects. How well this can be done will depend on the visibility of the defect and, if there are other objects in the area to be searched, the conspicuity of the defect. There are many different methods of lighting for visual inspection. All depend on the use of lighting to make the defect more visible and more conspicuous.

There are two features of industrial lighting that deserve special consideration from the lighting designer. They are the widespread practice of shift work and the increasing number of self-luminous displays used in industry. Lighting can, in principle, be used to shift the phase of the circadian timing system and thereby increase the speed with which adaptation to working at night is achieved, although to do so requires careful control of light exposure over the whole 24 h. A compromise approach of partial adaptation to shift work has also been proposed. A third approach is to abandon attempts at adaptation and to increase alertness at night by short duration exposures to high light levels. As for the increasing use of self-luminous displays, the problem with this is the risk that veiling reflections will reduce the visibility of the display. This problem can be overcome by careful attention to the light distribution or by shielding the display.

9 Escape Lighting

9.1 INTRODUCTION

Most countries have legal requirements that make it obligatory to provide an adequate means of escape in buildings where work is done and/or to which the public routinely has access. Emergency lighting is an essential part of an adequate means of escape. Emergency lighting can have three roles: escape, shutdown and continued operation. Escape lighting is lighting that is designed to ensure either the safe and rapid evacuation of a building or the ability to move to a place of refuge. To achieve this, escape lighting is designed to define the escape routes so that the occupants know which way to go and to illuminate the escape routes so that the occupants can move along them quickly and safely. Escape lighting is not designed to enhance the ability of either the occupants or the rescue services to deal with the emergency, other than to illuminate the positions of alarm points and firefighting equipment. Shutdown lighting is emergency lighting designed to enable the people involved in a high-risk process or situation to carry out an appropriate shutdown procedure before leaving. Shutdown lighting should provide an illuminance of not less than 10% of the normal lighting and never less than 15 lx, within 0.5 s of the electricity supply failing and for as long as the risk exists (SLL, 2006a). Standby lighting is used in parts of a building or site where, even in an emergency, activities should continue substantially unchanged, such as an operating theatre at a hospital. Standby lighting is usually powered from an emergency generator and should provide an illuminance similar to that provided under normal operating conditions. This chapter is concerned with escape lighting.

9.2 ESCAPE LIGHTING IN CONTEXT

Escape lighting is part of an emergency escape system. A well-researched emergency is the occurrence of fire. Research on the behaviour of people in fires (Bryan, 1999; Kuligowski, 2009; Kobos et al., 2010) has revealed a consistent pattern of response. The first stage is recognition; the second, action; and the third, escape. Recognition is usually associated with a high level of ambiguity. Investigations of fires occurring in prisons, nursing homes, hospitals and hotels have all shown that recognition of the existence of a severe fire is often dangerously delayed. For example, in the first World Trade Center tower attack on 11 September 2001, the median time to initiate evacuation after the impact was 3 min for occupants up to the 76th floor and 5 min for those on floors nearer but still below the impact zone starting on the 92nd floor (Averill et al., 2005).

Once the occurrence of a fire is recognized, there are a number of actions open to the people in the building: contacting others, fighting the fire, seeking refuge or leaving the building. A person tends to choose a course of action depending on the role the individual plays in an organization. For example, Best (1977) reported that in the Beverly Hills Supper Club fire, in which 164 people died, the waitresses showed people out through the smoke but only people who were seated at the tables for which they were normally responsible. Another factor that influences the choice of action is the presence of other members of the social group. In the Summerland Leisure Complex fire, in which 50 people died, there is evidence that parents looking for children were more likely to escape because the search took them away from the fire (Sime and Kimura, 1988).

The third stage comes down to a choice between attempting to escape, seeking out a refuge or staying and protecting oneself in place until rescued (Proulx, 1999). If the decision is to try to escape or to seek a refuge, it is necessary to identify the escape route. Escape lighting is important for defining and revealing the escape route, but this alone is not enough to ensure escape. The maximum volume of traffic that an escape route can handle and the complexity of the route also need to be considered. There are several models of evacuation that can be used to assess the life safety performance of a building (Kuligowski and Peacock, 2005).

To summarize, three types of information are needed for building occupants to escape in an emergency. They are as follows:

- Information on the presence of a hazard, including its nature and location
- Information on the recommended course of action
- Information on how to carry out the recommended course of action

9.2.1 Information on the Presence of a Hazard

Ideally, information on the presence of a hazard should be both immediate and complete. In some situations, the necessary information is provided by the hazard itself. A domestic fat fire is obvious to the person doing the cooking. Where it is not obvious is when the hazard occurs remotely from many of the occupants. For most buildings, it may be argued that the sounding of an audible fire alarm in the building and/or a sudden power failure should be interpreted as a reason for leaving the building. However, Tong and Canter (1985) and Geyer et al. (1988) have shown that only 10%–20% of people interpret the sounding of an audible fire alarm as a reason for immediately leaving the building. A plausible reason for this lack of response is the ambiguity of the message (Proulx, 2000a). Possible interpretations of the sounding of the fire alarm, without any other signs of fire, are that it is a false alarm, an unscheduled fire drill, a test of the fire alarm system, a small fire which can be easily controlled or a fire a long way away representing no hazard. Unless there is other evidence of the seriousness of the hazard, such as smoke, most people's response is either to investigate further or to carry on as normal until further information is available.

If this interpretation of the lack of response to a fire alarm is correct, providing more information would probably increase the number of people responding. Geyer et al. (1988) examined people's interpretation of a number of different modes of presenting messages concerning an outbreak of fire. The modes examined were 3D and 2D graphic displays, text displays, a speech warning and a conventional fire

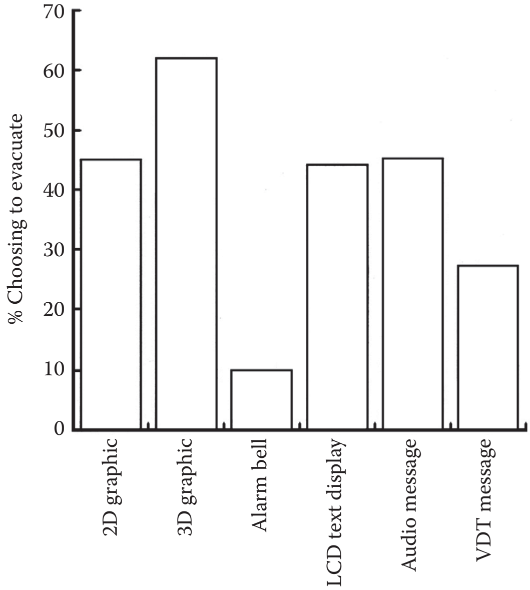


FIGURE 9.1 The percentage of people choosing to evacuate for different means of presenting information about a fire. (After Geyer, T.A.W. et al., An evaluation of the effectiveness of the components of informative fire warning systems, in J. Sime, ed., *Safety in the Built Environment*, E. & F.N. Spon, London, U.K., 1988.)

alarm bell. The 3D and 2D displays indicated the location of the fire and the location of exits. The text displays and the audible message gave the location of the fire and the instruction to leave immediately. The participants took longer to acquire the message from the 3D and 2D graphic displays than from the other modes, but there was no difference in the total response time. Thus, the time taken to receive the message and decide on an appropriate action was the same for all modes of presenting the message. What was different was the percentage of participants interpreting the display as a genuine fire warning and the percentage choosing to leave the building (see Figure 9.1). This study suggests that giving more information is likely to increase the frequency of the desired response, the percentage choosing to evacuate being much lower for the fire alarm bell than any of the other modes.

Given that more extensive information on a fire is desirable, the next question to consider is who should have that information. An approach sometimes recommended is to limit the information supplied to the occupants of the space in order to avoid panic and to allow an organized evacuation. However, Fahy et al. (2009) suggest that panic is rather a rare event in fires. For example, in the Beverly Hills Supper Club fire, prior to the entry of thick smoke into the room, the evacuation was orderly. If panic does not occur until an obvious and immediate hazard presents itself, there is no case for restricting information to avoid panic. Those who cannot see an immediate hazard are not likely to panic and may be encouraged to act rationally while there is time. Those who face an immediate and obvious risk of being burnt to a crisp are not likely to be listening to information messages anyway.

These findings as to how people react to fire alarms lead to the conclusion that the more information presented to building occupants about a fire and the faster it is presented, the more likely they are to choose a rational action. Present day communication technology makes it relatively easy to provide much more information about a hazard than is available through the sounding of a fire bell.

9.2.2 Information on the Recommended Course of Action

Once the reality of the situation is recognized, the building occupant has to decide on an appropriate course of action. The decision made is likely to be determined by a number of different factors, such as

- The occupant's perception of the hazard
- The occupant's concerns
- The occupant's place in the social organization in the building

The occupant's perception of the hazard includes such information as where it is, whether it is likely to spread and how much time is available. Interestingly, 90% of the survivors of the second World Trade Center tower attack started to evacuate during the 16 min between the first and second towers being hit. This explains why only 11 occupants of the second tower who were initially below the 78th floor, the lowest floor of impact, did not survive the attack (Averill et al., 2005).

The occupant's concerns may vary from the need to flee from immediate danger to tackling the hazard, warning other people, summoning help, securing belongings and ensuring the safety of close relatives. The occupant's place in the social organization will influence his/her concerns. Canter et al. (1980) showed that in hospital fires, who investigates and who assists are determined by the organizational hierarchy. Wood (1980) showed that the roles of husband and wife tended to be maintained in domestic fires. Both Bryan (1977) and Wood (1980) collected data on behaviour from a large number of people involved in fires. Their results show a wide diversity of behaviour, as might be expected from the list of influences given earlier.

These observations again suggest that it would be useful to provide more information so that occupants could choose the appropriate behaviour. At present, the most widely used approach is to teach only one behaviour, evacuation. Unfortunately, the rigour with which this is carried out and the advice given vary from place to place. Large facilities with internal communication systems have used auditory messages to guide people to an appropriate action (Proulx and Koroluk, 1997; Proulx, 1998). Such systems can be automated or manual. Automated systems can provide guidance to building occupants, but if they are to be helpful, they need to be sophisticated enough to match the guidance to the specific emergency situation. A manual system allows emergency personnel to talk to building occupants through a public address system. This certainly provides flexibility, but its value depends critically on the information available to the person controlling the communication network. If he/she is uninformed or uncertain what to do, then confusion can result. For example, in the second World Trade Center tower attack, 2 min before the tower was hit, occupants were instructed to return to their offices, but within 1 min of impact were instructed to evacuate if conditions on their floor warranted that decision. Later announcements were not heard by many occupants (Averill et al., 2005). Proulx (2000b) reviews a number of strategies whereby occupants of a large building can be guided to an appropriate response to a fire alarm signal.

9.2.3 Information on Carrying Out the Recommended Course of Action

Given that the recommended course of action is to evacuate the building or to move to a specified refuge, there are two pieces of information required by the occupant: which way to go and how to move safely over the chosen route. This is where escape lighting has a role to play. The exit sign is the primary means of providing information on which way to go and the escape route lighting is important in allowing people to see well enough so that they can move safely over the chosen route. The loss of life that can occur when insufficient or misleading information is provided by the escape lighting is revealed in Willey (1971), Lathrop (1975), Bell (1979) and Anon (1983). Of course, the presence of an exit sign simply conveys the information that there is a route out of the building. It does not indicate whether or not that route is a safe one to follow. To know that requires that much more information about the location and nature of the hazard be given to the occupant, as discussed earlier.

9.3 OPERATING CONDITIONS

The conditions in which escape lighting has to operate can be considered on two dimensions: the availability of electrical power and the presence of a turbid medium, such as smoke. There are four possible combinations of these conditions:

- The power–no smoke condition corresponds to the conventional operating state of the building. In this condition, the normal electric lighting is available and visibility is unaffected by smoke, so there is no need for escape lighting to be operating.
- The no power–no smoke condition corresponds to a power failure or shutdown in which the building needs to be evacuated, but there are no turbid media present. In this condition, the conventional electric lighting is not available, but visibility is unaffected by the absorption and scattering of light. In this condition, the escape lighting should be operating.
- The power–smoke condition occurs when there is a fire, but the electrical circuits are still operating. In this condition, the normal electric lighting is available, but visibility is limited by the scattering and absorption of light due to smoke. In this condition, the escape lighting should be operating.
- The no power–smoke condition corresponds to a fire in which the power supply is disabled or shutdown. In this condition, the conventional electric lighting is not available, and visibility is further restricted by the scattering and absorption of light due to smoke. In this condition, the escape lighting should be operating.

This brief consideration of the possible operating conditions shows that for three out of the four possible combinations, escape lighting is required.

9.4 EXIT SIGNS

Exit signs are designed and positioned to indicate which way to go to get out of the building. Detailed specifications exist for exit signs in many countries. In the United States, the word 'EXIT' is commonly used. The specification determining what constitutes an exit sign covers the height and width of the letters forming the word EXIT, the spacing between the letters and the size, shape and location of any directional indicators. Details of these quantities, together with the required photometric characteristics, are given in the Life Safety Code (NFPA, 2012). In the European Union, which currently has 28 members speaking almost as many languages, a pictogram, consisting of a white, running stickperson, a solid white rectangle signifying a door and a white arrow indicating the direction of movement, all on a green background, is used. Details of the required form and size of the pictogram are given in ISO Standard 7010:2011 (ISO, 2011). The photometric requirements for exit signs used in the United Kingdom are summarized in Table 9.1.

But simply specifying the necessary geometrical characteristics for an exit sign is not enough. Schooley and Reagan (1980a,b) conclude that in order to assess the visibility of an exit sign, it is also necessary to specify the maximum distance at which the sign is to be read. The Life Safety Code (NFPA, 2012) covers this requirement by stating that no point on an escape route should be more than 30 m (100 ft) from an exit sign. Collins (1991) examined the distances at which people could detect and correctly identify the words on an externally illuminated exit sign conforming to the dimensions of the Life Safety Code as part of a larger study of the visibility of directional indicators. The signs used were illuminated to 54 lx, the minimum specified for externally illuminated signs. All 20 observers used were able to correctly identify the word 'EXIT' at distances greater than 30 m (100 ft). These results suggest that the physical and photometric specifications for exit signs given in the Life Safety Code are consistent with the demand that no one should be more than 30 m (100 ft) from an exit sign when on an escape route.

The question that now needs to be considered is how commercially available exit signs perform. Collins et al. (1990) evaluated 13 different internally illuminated exit signs using various light sources. All the exit signs met the Life Safety Code specifications for physical dimensions and contrast, but they varied greatly in luminance.

TABLE 9.1
Photometric and Timing Requirements of Exit Signs for Use in the United Kingdom

Minimum luminance of safety colour: 2 cd/m^2
Maximum/minimum luminance ratio of colour: <10
Range of luminance ratio of white to colour: >5 but <15
Minimum response time: 50% of design luminance in 5 s, 100% in 60 s
Minimum duration: 60 min

Source: Society of Light and Lighting, *Lighting Guide 12: Emergency Lighting Design Guide*, SLL, London, U.K., 2006a.

Even in a dark room, some of the signs viewed from a distance of 19 m (63 ft) were barely visible. The situation became worse when lighting was introduced into the room. When an illuminance of 54 lx fell on the face of these internally illuminated signs, as might occur when a luminaire forming part of the escape route lighting is operating close to the exit sign, the luminance contrast of some exit signs was reduced to below the Life Safety Code standard of 0.5. This suggests that should an emergency arise that requires evacuation, some exit signs would be of limited value.

This conclusion is supported by other measurements of readability of exit signs (LRC, 1994, 1995). In these measurements, observers saw 60 different commercially available, internally illuminated exit signs. The exit signs used five different light sources: CFL lamps, incandescent lamps, an electroluminescent panel, light-emitting diodes (LEDs) and radioluminescent tubes (see Section 1.7.5). The exit signs were in four different formats: panel, stencil, matrix and edge-lit. In a panel exit sign, both the letter and the background are luminous. In a stencil exit sign, the letters are transparent and the background is opaque so only the letters are luminous. In a matrix exit sign, the letters are formed by points of light and the background is opaque. In an edge-lit exit sign, light from an enclosed source is directed through a transparent plate that has the letters etched in or attached to its surface. The sign face that forms the background to the letters appears luminous, although how luminous will depend on what lies behind the sign. The 60 exit signs used were presented at the end of a long corridor, one at a time, in a mirror box (Figure 9.2). By placing the exit sign in the mirror box at different positions, four different orientations of the word 'EXIT' could be obtained. For each exit sign, the observer started to walk towards the exit sign from a distance of 50 m (165 ft). The distance at which the observer could correctly identify the orientation of the exit sign was recorded. Figure 9.3 shows the percentage of observers who could correctly identify the orientation of the exit sign at 30 m (100 ft), plotted against the mean letter luminance, with the corridor lighting on and off. The corridor lighting provided an average illuminance of 340 lx on the floor of the corridor when on. It is clear from Figure 9.3 that a low letter luminance leads to difficulty in reading the exit sign at 30 m (100 ft). The letter luminance can be closely related to the nature of the light source used to internally illuminate the exit sign. The radioluminescent and electroluminescent exit signs were difficult to be read at 30 m (100 ft) because of their low letter luminance.

As for exit signs lit by the other light sources, in some form, all can be read at 30 m (100 ft) by all observers. However, at the same letter luminance, some exit signs fail to achieve readability by 100% of observers, while others using the same light source succeed. This implies that other factors besides mean letter luminance are important to readability. Inspection of the detailed measurements indicated that such aspects as the uniformity of the letter luminance and the luminance contrast of the letters against the background also influenced the readability of the sign. There was no consistent difference in readability for different sign formats, that is, for panel, stencil, matrix or edge-lit formats.

It is important to note that the results shown in Figure 9.3 were collected several years ago. Since then, there have been marked developments in the luminous efficacy of LEDs and in electroluminescent sources, now marketed as light-emitting capacitors. The point to note is that the readability of an exit sign is determined by

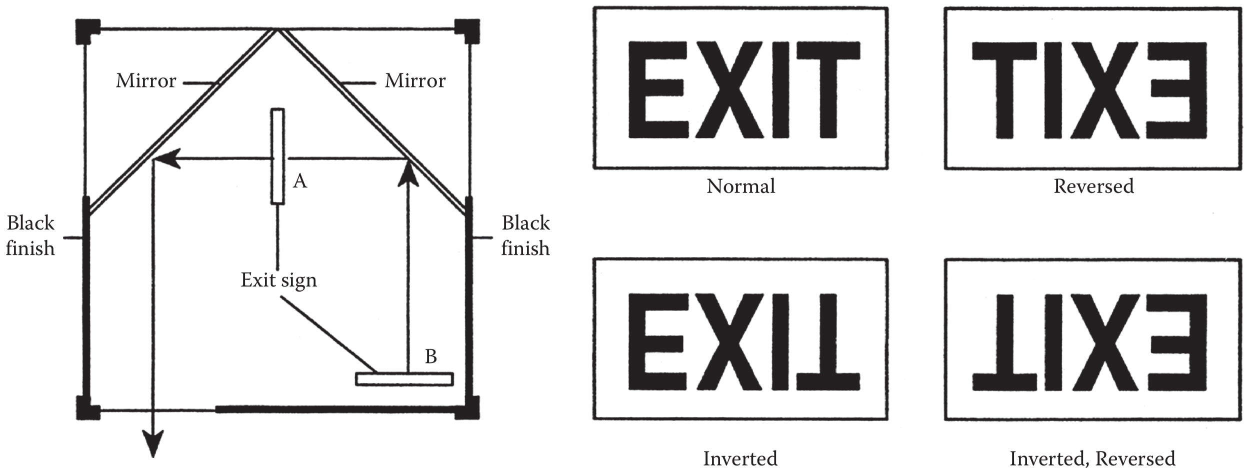


FIGURE 9.2 The mirror box used in the measurement of readability of exit signs. By placing the exit sign in the mirror box at positions A or B, the right way up or upside down, the word EXIT can be made to appear in the four different orientations shown. (After Lighting Research Centre [LRC], *Specifier Reports: Exit Signs*, LRC, Troy, NY, 1994.)

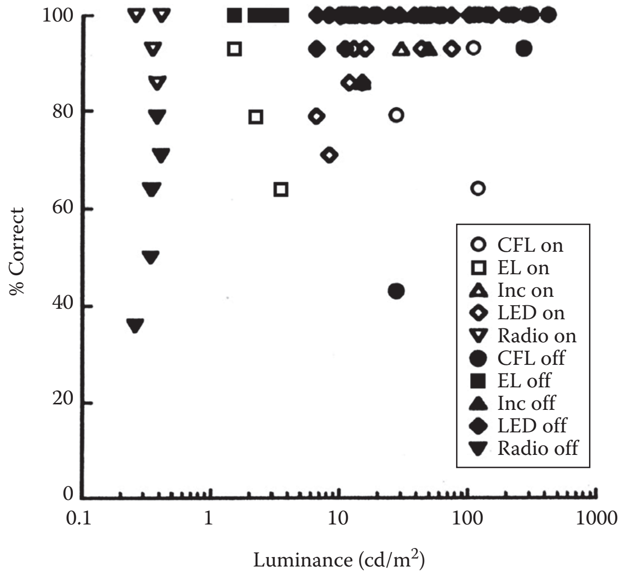


FIGURE 9.3 The percentage of observers able to detect the correct orientation of an exit sign at 30 m (100 ft) plotted against the average luminance of the legend of the exit sign. Five different light sources were used in the exit signs: CFL, compact fluorescent; EL, electroluminescent; Inc, incandescent; LED, light-emitting diodes; Radio, radioluminescent. Measurements were made with the normal corridor lighting on (open symbols) and off (filled symbols). (After Lighting Research Centre [LRC], *Specifier Reports: Exit Signs*, LRC, Troy, NY, 1994; Lighting Research Centre [LRC], *Specifier Reports Supplements: Exit Signs*, LRC, Troy, NY, 1995.)

the stimulus it presents to the visual system, not by the technology or format used to create that stimulus. It is only when a specific technology or format consistently limits some critical aspect of the visual stimulus that the technology or design should be considered unsuitable for use in exit signs.

Given that the function of an exit sign is to tell the observer the way to go, then some exit signs also need to have one or two directional indicators. Collins (1991) examined the distance at which various forms of directional indicator could be correctly detected. She established that out of five different forms of directional indicator arrow, all of the same vertical size, the chevron was most often correctly identified at the greatest distance. In further studies, she showed that the factors influencing the distance at which chevron directional indicators could be correctly identified were the area and colour of the chevron; the greater the area and the use of red or green rather than grey tended to increase the distance at which the direction indicated by the chevron could be correctly identified. Boyce and Mulder (1995), using the mirror box approach discussed earlier, confirmed the superiority of the chevron as a directional indicator, within the constraint that it had to fit within conventionally sized exit signs.

While readability is an important function of an exit sign, it is of little value if the sign cannot be found first among all the other information presented to the visual system. This is unlikely to be a problem in the no-power condition because then the exit sign will be one of the few signs still operating. However, when normal electrical power is available, all the other signs and luminaires will be operating. Jin et al. (1987) examined the factors affecting exit sign conspicuity using a computer image of a scene. As might be expected, the location and the size of the sign were important determinants of conspicuity. What was also important was the presence or absence of other signs of the same colour as the exit sign. Conspicuity was enhanced when none of the other signs were of the same colour as the exit sign. This supports the value of having an exit sign of a unique but well-known colour. Jin et al. (1985) also examined the effect on conspicuity of flashing an exit sign twice a second. People were asked to rate the conspicuity of the flashing sign relative to a non-flashing sign in a large shopping mall. The results obtained showed that flashing was effective in increasing conspicuity for signs which were visible but not conspicuous. Flashing made little difference to the conspicuity of large signs which were already conspicuous because of their size relative to other signs in the mall, nor to small signs which were too small to be recognized as exit signs from the viewing position. These data were obtained in a power–no smoke condition. It would be interesting to know how effective flashing would be when applied to exit signs in a no power–smoke condition, where the scattering of light in the smoke might cause confusion rather than provide information (Malven, 1986). The Life Safety Code (NFPA, 2012) encourages conspicuity of exit signs by insisting that 'no decorations, furnishings, or equipment that impairs visibility of an exit sign shall be permitted. No brightly illuminated sign (for other than exit purposes), display or object in or near the line of vision to the required exit sign of such a character as to detract attention from the exit sign shall be permitted', and by allowing exit signs to flash on and off upon activation of the fire alarm system.

This brief discussion of conspicuity suggests that a coloured exit sign is more likely to be seen than a colourless exit sign, but what colour is best? Different countries used different colours for exit signs. Some states in the United States demand red letters in an exit sign, while others insist on green. The European Union pictogram has white elements on a green background. Enthusiasts for one colour or another will produce rationalizations such as red means stop and green means go or red means danger and green means safety. There is no evidence to support any of these rationalizations. Rather, what seems to matter most is familiarity with the colour of an exit sign. This is one justification for having common exit sign formats applied over whole continents.

9.5 ESCAPE ROUTE LIGHTING

9.5.1 Ceiling- and Wall-Mounted Luminaires

An escape route is a clearly defined, permanently unobstructed route out of a building (SLL, 2006a). Escape route lighting is designed to allow people to move over the escape route quickly and safely. Escape route lighting is usually provided either by defining some of the luminaires used in the normal lighting as emergency luminaires and arranging for them to continue to operate when the normal power supply fails or by providing special luminaires that only operate when the normal power supply fails or a fire is detected. In both approaches, the luminaires are designed and spaced to provide a minimum illuminance along the escape route. Different countries have different criteria for escape route lighting. In the United States, the Life Safety Code specifies an initial average illuminance of 11 lx on the floor of corridors, passageways, stairways, stair landings, ramps and escalators, with a minimum illuminance at any point of 1.1 lx (NFPA, 2012). In the United Kingdom, the horizontal illuminance at floor level on the centre line of a defined escape route should be not less than 0.2 lx (SLL, 2006a). Such differences raise the question of what is an appropriate illuminance for an escape route.

Ouellette and Rea (1989) examined a series of measurements of peoples' ability to move over escape routes lit to different illuminances by ceiling-mounted luminaires, with exit signs to indicate the way to go. Independent studies by four authors (Nikitin, 1973; Simmons, 1975; Jaschinski, 1982; Boyce, 1985) showed that a mean illuminance on the floor of the escape route of at least 0.5 lx was sufficient to ensure movement over the escape route without collisions with objects. The results of Simmons (1975), Jaschinski (1982) and Boyce (1985) can also be compared by using speed of movement over the escape route as a common measure. Figure 9.4 shows the relationship between the speed of movement and the mean illuminance on the floor of the escape route, for young and older participants. Simmons (1975) had an escape route that was effectively a network of corridors with steps and occasional obstructions formed from large cardboard boxes. Jaschinski (1982) formed an escape route through several interconnected small rooms with steps between the rooms. Boyce (1985) used a large open-plan office where participants had to find their way through

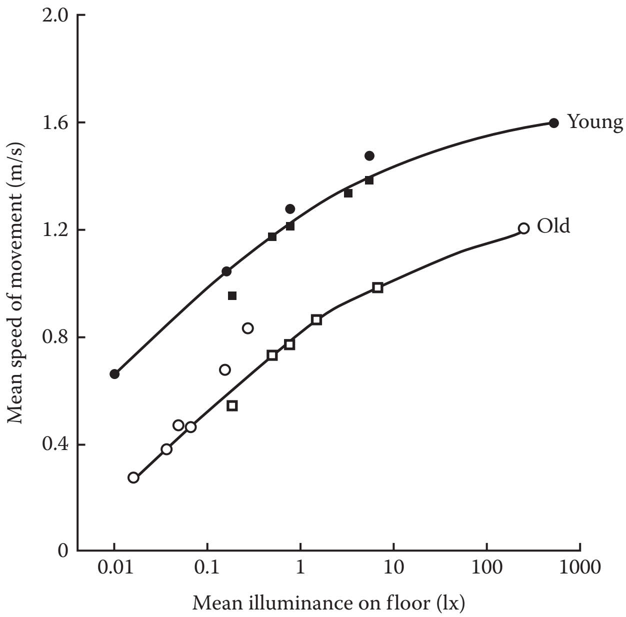


FIGURE 9.4 Mean speed of movement in cluttered or furnished spaces by young and old people, plotted against mean illuminance on the floor. (After Ouellette, M.J. and Rea, M.S., *J. Illum. Eng. Soc.*, 18, 37, 1989.)

the furniture to the door. Given that the three studies were carried out using different participants moving over very different courses, the agreement shown in Figure 9.4 is remarkable. What is clear from Figure 9.4 is that there is an accelerating decline in movement speed as illuminance is reduced from the highest mean illuminance used, which is typical of normal office lighting. At the minimum illuminance specified by the Life Safety Code of 1.1 lx, there is about a 19% reduction in movement speed for younger people and a 33% reduction for elderly people. At the minimum illuminance specified in the United Kingdom (SLL, 2006a) of 0.2 lx, the reduction in speed is about 32% for the young and 50% for the elderly.

Jaschinski (1982) and Boyce (1985) also obtained subjective assessments of satisfaction with the lighting of the escape route. Jaschinski (1982) found that his participants were satisfied at a mean illuminance of 3 lx. Boyce (1985) found that a mean illuminance of 7 lx was sufficient to ensure a high level of satisfaction. From these studies, it can be concluded that the initial mean illuminance recommended in the Life Safety Code (11 lx) is sufficient to ensure safe and speedy movement over the escape route in a clear atmosphere, provided a 10%–20% reduction in movement speed from that achievable in normal room lighting is acceptable. While this is useful information, it does not indicate the reason for the decline in movement speed. That there should be such a decline is obvious because in complete darkness, the only way the occupant can move over the escape route is by touch, and this is a slow and uncertain process. Figure 9.4 shows the compressive function expected for any relationship between an aspect of performance dependent on vision and illuminance, but what determines the illuminance at which the decline in movement speed begins to accelerate? One plausible answer to this question is the range of luminances over which neural adaptation can occur (see Section 2.3.1). Neural adaptation to a sudden change in adaptation luminance is very fast, of the order of fractions of a second. For larger changes of adaptation luminance, photochemical adaptation is necessary and this takes of the order of minutes, especially if vision is dependent on the operation of rod photoreceptors. Neural adaptation can cover a range of about two to three log units of luminance, which implies that for normal lighting providing an average illuminance of 400 lx on the floor, neural adaptation can take place down to an average illuminance of 4–0.4 lx. At lower illuminances, there will be a marked decrease in movement speed because of the delay caused by the time taken by the visual system to adapt to the lower luminances. This explanation implies that in situations where the occupants can be expected to already be adapted to low luminances, such as in cinemas and theatres, lower illuminances would be acceptable for escape route lighting.

Despite the emphasis given to mean illuminance on the escape route, it should not be thought that simply providing the specified mean illuminance is sufficient to ensure adequate escape route lighting. Other factors to be considered are the illuminance uniformity, the possibility of disability glare, the colour properties of the light sources used, the time duration for which the escape route lighting should be provided and, where the escape route lighting is not permanently lit, the time delay between the failure of the normal power supply and the ignition of the emergency lighting.

SLL (2006a) addresses the question of illuminance uniformity in two ways. First, it considers the variation across the width of the escape route by specifying that the minimum illuminance on the central band of the route, defined as at least 50% of the route width, should not be less than 0.1 lx. Second, it addresses variation along the length of the route by specifying that the ratio of maximum to minimum illuminance on the floor along the centre line of the escape route should not be more than 40:1.

Disability glare has the potential to make it difficult to see exit signs and any obstructions along the escape route. In SLL (2006a), disability glare is controlled by setting maximum luminous intensities from the escape route lighting luminaires within 60°–90° from the downward vertical, at all angles of azimuth, for level escape routes, and at all angles within the lower hemisphere for non-level escape routes (see Table 9.2).

To ensure accurate identification of safety colours, SLL (2006a) requires that the minimum Commission Internationale de l'Eclairage (CIE) general colour rendering index (CRI) of any light source used for emergency lighting is 40. This is not the only effect of light spectrum on the ability to move over the escape route. Although the illuminances used in recommendations for lighting escape routes are photopic illuminances, it is more than likely that when using the escape route the evacuee's visual system will be in the mesopic or even the scotopic state. Mulder and Boyce (2005) examined a worst case by measuring the ability of people to move through a black, obstructed space when the space was lit by different light sources to different illuminances. The different light sources used varied from the conventional fluorescent and incandescent to unusual narrow band LEDs. A performance metric was constructed based on the speed of movement and the number of collisions with obstacles. This took the form

$$PM = \frac{V}{(C + k)}$$

where

PM is the performance metric
V is the speed of movement over the escape route (m/s)
C is the number of collisions
k is a constant given by the speed over the escape route in normal lighting conditions (1.474 m/s)

TABLE 9.2
Maximum Luminous Intensity (cd) from Emergency Lighting Luminaires

Mounting Height, *h*, above Floor (m)	Maximum Luminous Intensity for Escape Route Lighting and Open Area Lighting (cd)
$h < 2.5$	500
$2.5 < h < 3.0$	900
$3.0 < h < 3.5$	1600
$3.5 < h < 4.0$	2500
$4.0 < h < 4.5$	3500
$h > 4.5$	5000

Source: Society of Light and Lighting, *Lighting Guide 12: Emergency Lighting Design Guide*, SLL, London, U.K., 2006a.

This constant has the effect of normalizing performance to the ambient lighting in which the fastest movement occurred and there were no collisions. Figure 9.5 shows the median performance metric plotted against the mean photopic illuminance and the mean scotopic illuminance on the floor for the different light sources. Clearly, performance is much more closely related to the scotopic illuminance than the photopic illuminance. What this means is that light sources with a lot of energy at the short-wavelength end of the visible spectrum are more suitable for escape route lighting than those with little. One way to quantify this is to consider the scotopic

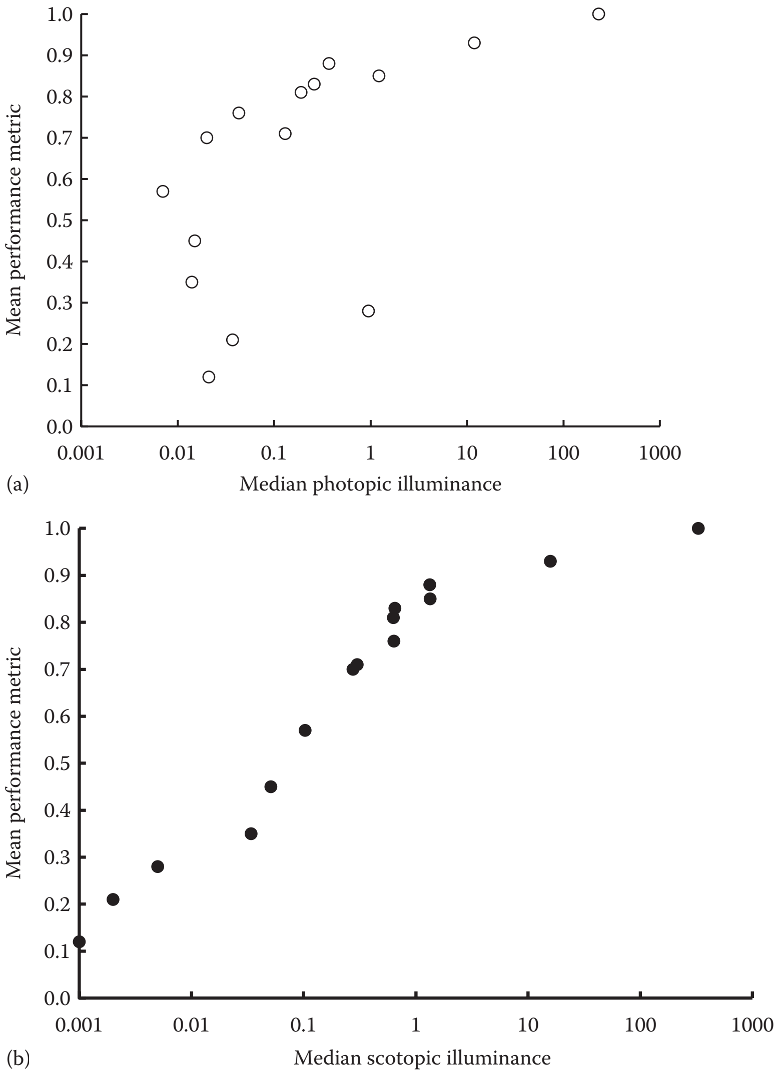


FIGURE 9.5 Mean performance metric plotted against (a) log median photopic illuminance and (b) log median scotopic illuminance. (After Mulder, M. and Boyce, P.R., *Lighting Res. Technol.*, 37, 199, 2005.)

illuminance as well as the photopic illuminance provided. For any given light source, the scotopic illuminance can be obtained by multiplying photopic illuminance by the scotopic/photopic ratio of that light source (see Section 1.6.4.5).

As for the timing of the escape route lighting, to allow adequate time for evacuation of a building, SLL (2006a) recommends that the escape route lighting should reach 50% of the design illuminance within 5 s and all the required illuminance within 60 s of the failure of normal lighting. Then, the illuminance on the escape route should be maintained above the specified minimum for at least 60 min.

The Life Safety Code (NFPA, 2012) deals with these factors by requiring that the maximum to minimum illuminance ratio of the escape route lighting should not be more than 40:1; the escape route lighting should be provided for 90 min in the event of a failure of normal lighting, although the mean illuminance is allowed to decrease to 6.5 lx with a minimum at any point of 0.65 lx, by the end of the 90 min. The Life Safety Code mentions neither the disability glare nor the colour properties of the light sources to be used. It does consider the delay time between failure of the normal power supply and the onset of the escape route lighting in general terms by saying that there should be no appreciable interruption of illumination during the changeover to another source of electricity. The only indication of what is appreciable is the requirement that where emergency lighting is provided by a generator, a delay of not more than 10 s is permitted.

The effect of different time delays on the ability to move over an escape route was studied by Boyce (1986) in an open-plan office. He found that given a low mean illuminance on the escape route of 0.16 lx, delaying the onset of the emergency lighting until 5 s after the normal lighting was extinguished ensured more rapid, steadier movement with fewer collisions once movement started than if the subject moved immediately following an instantaneous change from normal lighting to escape route lighting. However, the total time taken to leave the room was slightly longer than if the participants moved immediately following the instantaneous changeover. The faster, steadier movement with the 5 s delay occurs because the delay allows some visual adaptation to occur. How much adaptation is needed will depend on the difference between the adaptation luminance provided by the normal lighting and that provided by the escape route lighting. The smaller is this difference, the less adaptation is needed, so the less the benefit in terms of smoother and faster movement and the greater the penalty in terms of longer escape times, of having a time delay between the failure of the normal lighting and the onset of the escape lighting. While such understanding is interesting academically, given that the usual behaviour of people in fires is to hesitate before responding to an emergency signal unless there is obvious cause for alarm, worrying about whether the delay time should be 5 s or less is not the most important question to anyone concerned with improving fire safety in buildings.

Finally, it is necessary to consider how an occupant might get to an escape route. For small spaces, such as the rooms in a hotel where the corridor outside is the escape route, this is not a problem because the distance to be covered is small and the exit is obvious. For large spaces where there is fixed furniture, as in a concert hall, the lighting recommendations (SLL, 2006a) are for a minimum illuminance of 0.1 lx 1 m above the floor of the seated area, a maximum/minimum illuminance ratio on the plane 1 m above the floor of the seated area of less than 40, a minimum CIE general CRI of 40, 100% of the minimum illuminance to be available within 5 s of the electricity supply failing and a minimum duration of 60 min. For large spaces which are empty or where the furniture can be easily reconfigured, so there are many different possible directions of movement, the lighting recommendations (SLL, 2006a) specify a minimum illuminance on the empty floor of 0.5 lx excluding a 0.5 m wide perimeter band, a maximum/minimum illuminance ratio across the empty floor of less than 40, a minimum CIE general CRI of 40 and a minimum duration of 60 min. The onset time is given as 50% of the minimum illuminance within 5 s and 100% within 60 s of the electricity supply failing. Exit signs defining access to escape routes should be visible from all points in both types of open space.

9.5.2 Path Marking

An alternative approach to the lighting of escape routes is that of path marking. This approach aims to mark the escape route at frequent intervals, typically separated by a few centimetres, from a low mounting position, and to rely on the light from the path marking to illuminate the escape route (BSI, 1998, 1999).

This can be done using electrically powered devices, but a different technology of increasing interest is photoluminescent panels (Tonikian et al., 2006). These panels use a phosphor that absorbs photons of light, reradiating them later. The phosphor is produced as a powder and applied to paint, tape, ceramics or plastic. The phosphor is charged by incident light over a range of wavelengths determined by its chemistry, usually the UV and short wavelength visible. When there is no light incident on the panel, the photoluminescent panel continues to emit light, although the luminance of the panel declines, following a power law, over time (Webber and Hallman, 1989). Fortunately, this decline in luminance under conditions of darkness is paralleled by an increase in sensitivity of the visual system. Until the late 1990s, the phosphor used was zinc sulphide with copper and cobalt activating agents. Today, more efficient alkali earth aluminate phosphors are used that provide higher luminances for longer after the incident lighting is extinguished. A path-marking system based on photoluminescent panels is attractive because it requires no power supply, only incident illumination prior to the emergency. This means it is reliable in operation and easy to install in existing buildings. Significant numbers of survivors of the 2001 World Trade Center attack said they noticed the photoluminescent marking in the stairwells and found it helpful in evacuating the towers (Averill et al., 2005). This photoluminescent marking was installed after the bomb attack on the same buildings in 1993. Then, the explosion destroyed both the normal and the emergency power supplies and required people to evacuate the towers in darkness, a process that took more than 6 h.

Webber et al. (1988) studied the ability of people to move along a corridor and down a flight of stairs using either conventional ceiling-mounted escape route lighting or path marking using zinc sulphide-based photoluminescent markers. They found that the mean movement speed of people under the photoluminescent path marking was similar to that achieved at an illuminance of 0.2–0.3 lx from conventional escape route lighting on the stairway but was comparable with only about 0.05–0.10 lx for the corridor (Figure 9.6). Subjective assessments of how difficult it was to see where to go showed that on the staircase, the photoluminescent installation was considered less difficult than the conventional escape route lighting, but in the corridor, it was

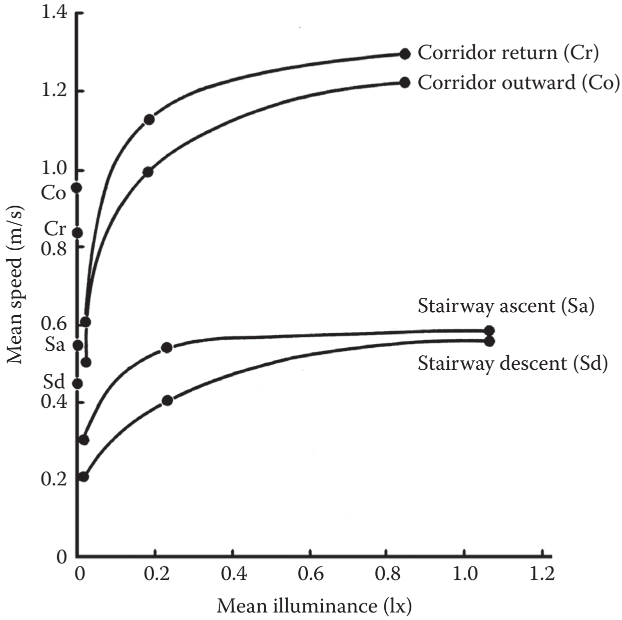


FIGURE 9.6 Mean speed of movement along a corridor and up and down a flight of stairs, under conventional ceiling-mounted escape route lighting and using photoluminescent path marking alone, plotted against the mean illuminance on the floor. The mean speeds for the photoluminescent path marking are plotted at zero illuminance. (After Webber, G.M.B. et al., *Lighting Res. Technol.*, 20, 167, 1988.)

more difficult. The reason for this changeover in difficulty between the two escape lighting types was the density and placing of the photoluminescent material. This is an important point. For any path-marking system to be effective, it has to mark the path completely and unambiguously. Thus, the placement of photoluminescent material calls for considerable care to ensure continuity of guidance. Given this, there is considerable potential for the use of photoluminescent materials in path-marking systems (Proulx et al., 2000). Indeed, photoluminescent marking of exit stairs is now a requirement for all buildings over 75 ft high in New York City.

Other forms of path marking have used powered electroluminescent panels, miniature incandescent lamps and LEDs as light sources. Aizlewood and Webber (1995) measured people's ability to move over an escape route consisting of a corridor and a staircase, for three different path-marking installations and traditional escape route lighting from ceiling-mounted luminaires. The path-marking systems used zinc sulphide-based photoluminescent panels, electroluminescent track and miniature incandescent track, all mounted close to the skirting board in the corridor and parallel to the pitch line of the stairs on the staircase. Figures 9.7 and 9.8 show the measured mean speeds of movement in the corridor and on the stairs for the different lighting systems plotted against the mean illuminance on the floor or steps. It can be seen that there is little difference in mean speed between the conventional ceiling-mounted escape lighting and the path-marking systems at mean illuminances of 1 lx

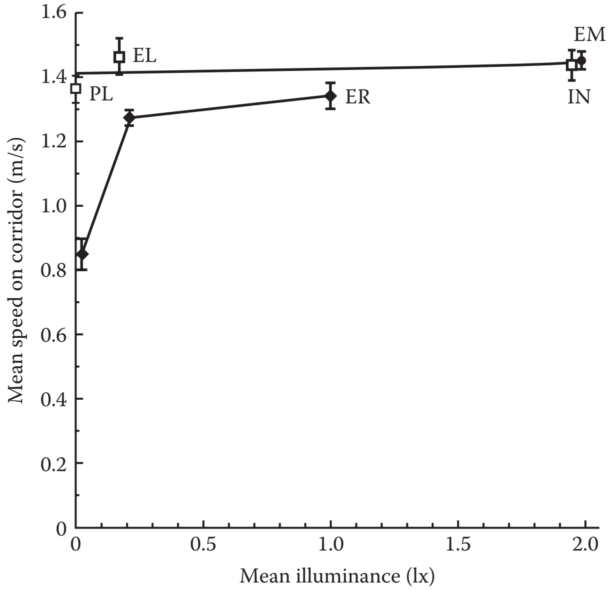


FIGURE 9.7 Mean speed, and the standard error of the mean, for movement along a corridor lit using electroluminescent (EL), incandescent (IN) or photoluminescent (PL) low-mounted path-marking systems or conventional ceiling-mounted escape route lighting (EM), plotted against the mean illuminance on the floor. Also shown for comparison purposes are the mean speeds over the same corridor lit by ceiling-mounted escape route (ER) luminaires to lower illuminances. These mean speeds were measured for a different group of subjects in an earlier experiment (Webber et al., 1988). (After Aizlewood, C.E. and Webber, G.M.B., *Lighting Res. Technol.*, 27, 133, 1995.)

and more, but as the mean illuminance was decreased below about 0.2 lx, the path-marking systems allowed speed to be maintained at a higher level than did the ceiling-mounted escape route lighting. As for the differences between the path-marking systems, the only consistent difference is the slightly lower speeds achieved under the unpowered photoluminescent path marking relative to the powered incandescent and electroluminescent systems. It is important to remember that these results were obtained using zinc sulphide-based photoluminescent marking. It may well be that more modern photoluminescent panels that produce higher luminances would have eliminated this difference.

The participants also walked the escape route with four obstacles placed on the path, the four obstacles being a life-sized dummy, a wooden stool, a wastepaper bin and a buff-coloured folder. Video recordings of the participants' movements over the escape route showed that under the powered electroluminescent and incandescent path-marking systems and the traditional ceiling-mounted escape route lighting system, many participants saw the obstacles from a distance and deliberately avoided them, but under the photoluminescent system, many participants did not see the obstacles until they were very close to them or actually touched them. For the dummy, stool and bin, the percentage of participants detecting these obstacles was 88%, 73%, 69% and 46% for the miniature incandescent path-marking system, the ceiling-mounted escape route

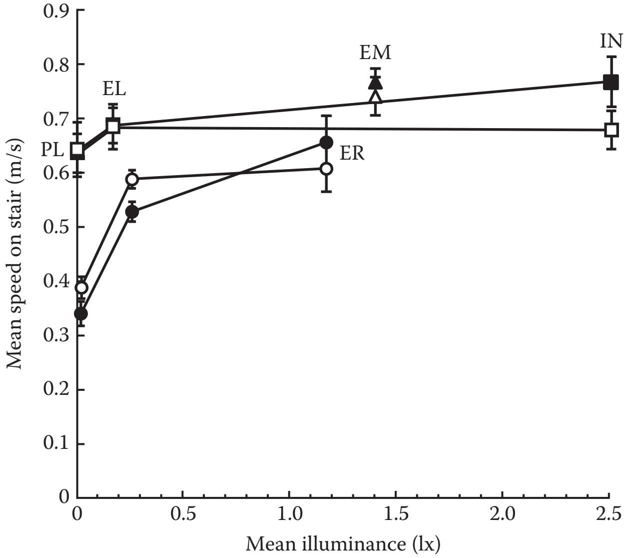


FIGURE 9.8 Mean speed, and the standard error of the mean, for movement up and down a flight of stairs lit using electroluminescent (EL), incandescent (IN) or photoluminescent (PL) low-mounted path-marking systems or conventional ceiling-mounted escape route lighting (EM). Also shown for comparison purposes are the mean speeds over the same flight of stairs lit by ceiling-mounted escape route (ER) luminaires providing lower illuminances. These mean speeds were measured for a different group of subjects in an earlier experiment (Webber et al., 1988). (After Aizlewood, C.E. and Webber, G.M.B., *Lighting Res. Technol*., 27, 133, 1995.)

lighting, and the electroluminescent and photoluminescent path-marking systems, respectively. From these results, it was concluded that low-mounted path-marking systems could ensure a speed of movement as good as or better than traditional ceiling-mounted escape lighting. However, the difficulty in detecting the obstacles under the photoluminescent path-marking system suggests that simply marking the path is not enough. The escape route also needs to be illuminated. Aizlewood and Webber (1995) suggest a minimum illuminance on the floor of an escape route of 0.1 lx. This can be provided by a path-marking system if it has sufficient light output, which may be the case with modern photoluminescent materials. Guidance on both electrically powered and non-electrically powered path-marking systems is available (Webber and Aizlewood, 1993b; BSI, 1998, 1999; SLL, 2006a; PSA/PSPA, 2008).

All the studies of path marking mentioned earlier have been done measuring the performance of one person at a time. Proulx and Benichou (2009) report two studies of mass evacuation of an office building using photoluminescent marking in the stairwells. The first study took place in a 13-floor building, each floor being divided into four quadrants with one windowless stairwell serving each quadrant. Stairway A had conventional emergency lighting providing a mean illuminance of 57 lx on the stairs. Stairway B had the normal stair lighting providing a mean illuminance on the stairs of 245 lx. Stairway C had a zinc sulphide-based photoluminescent system only, and stairway D had emergency lighting providing 74 lx and a zinc sulphide-based photoluminescent system. The photoluminescent panels had a luminance of 3.2 mcd/m^2

TABLE 9.3
Mean Speeds down a Stairway under Four Different Lighting Systems, the Number of People Using Each Stairway and the Percentage of People Considering the Lighting Very Good and Acceptable or Poor and Dangerous

Lighting (Stairway)	Mean Speed (m/s)	Number Using	% Very Good and Acceptable	% Poor and Dangerous
Photoluminescent marking only (C)	0.57	144	70	30
Full normal lighting (B)	0.61	101	100	0
Escape lighting at 57 lx (A)	0.70	82	93	7
Escape lighting at 74 lx and photoluminescent marking (D)	0.72	65	100	0

Source: After Proulx, G. and Benichou, N., *Photoluminescent Stairway Installation for Evacuation in Office Buildings*, Publication NRCC-52696, National Research Council Canada, Ottawa, Ontario, Canada, 2009.

after 60 min. An unannounced evacuation drill was implemented in which 392 people left the building. On exiting the building, everyone was given a questionnaire. Of the 392 who left the building, 216 returned the questionnaire. Table 9.3 shows the mean speed of movement down the stairs, the percentage of people considering the different stairway lighting systems very good and acceptable or poor and dangerous and the number of people using each stairway. Clearly, the fastest speed and the highest percentage considering the lighting of the stairwells very good and acceptable were obtained for the stairwell with both powered escape route lighting and the photoluminescent system (D). Conversely, the stairway with only the photoluminescent system (C) showed the slowest speed and 30% of people using it considered the lighting poor and dangerous. At first, it would seem that these findings support the view that photoluminescent systems are suitable for supplementing powered escape route lighting but should not be used alone. However, there is one feature of these results that suggests caution in drawing this conclusion and demonstrates the difficulty that can occur when interpreting the results of relatively uncontrolled field trials. This is the number of people using each stairway. Examination of Table 9.3 will show that the more people using the stairway, the slower the speed, a relationship exacerbated by the presence of three firefighters ascending stairway C and forcing the people descending to move into a single line.

The second study took place in another office building with 13 floors. Four windowless stairways were used. One (stairway C) had powered emergency lighting providing an average illuminance of 37 lx. The other three had three different layouts of photoluminescent path marking, all based on alkali earth aluminate phosphors. These photoluminescent materials produced a luminance of 7 mcd/m^2 after 60 min of darkness, more than twice the luminance of the zinc sulphide-based materials at the same time. Again, an unannounced evacuation was initiated and the time taken to descend the stairs was measured, but a different question was asked. This time, the question sought people's opinions about the visibility in the stairwell used.

TABLE 9.4
Mean Speed down a Stairway under Four Different Lighting Systems, the Number of People Using Each Stairway and the Percentage of People Considering the Visibility in the Stairwell Excellent and Good or Not Very Good and Poor

Lighting (Stairway)	Mean Speed (m/s)	Number Using	% Excellent and Good	% Not Very Good and Poor
Photoluminescent marking, handrails and L-shape down the edge of stairs (A)	0.66	345	50	50
Escape lighting at 37 lx (C)	0.66	278	56	44
Photoluminescent marking, handrails and 1″ strip across each step (E)	0.40	287	67	33
Photoluminescent marking, handrails and 2″ strip across each step (G)	0.57	281	62	38

Source: After Proulx, G. and Benichou, N., *Photoluminescent Stairway Installation for Evacuation in Office Buildings*, Publication NRCC-52696, National Research Council Canada, Ottawa, Ontario, Canada, 2009.

Table 9.4 shows the mean speed in each stairway, the percentage considering the visibility excellent and good or not very good and poor and the number of people using each stairway. The most interesting point about these results is that the mean speed is similar for one form of photoluminescent marking (stairway A) and conventional escape route lighting (stairway C) when the number of people using the stairways is higher for the photoluminescent system. The stairways fitted with the two other forms of photoluminescent marking carried similar numbers of people, but they achieved slower speeds. This may have been due to the layout of the marking, but again caution is needed before drawing this conclusion. In the stairwell with the slowest speed (stairway E), it was reported that speed was limited by the presence of an obese person moving sideways down the stairs one step at a time and taking up the full width of the stair. Another factor limiting speed in all stairwells was the tendency of 80% of people to hold onto the handrails. This ensured people were moving in single file, which limited speed to that of the slowest person. There were even situations where people were observed holding onto both handrails so that no one could pass. As for the question on visibility, there was no statistically significant difference between the four stairways, none of them being particularly effective, although how much this is due to the crowding that occurred is open to question.

These two field studies support three opinions. The first is that, provided care is taken with layout, photoluminescent marking alone is close to being an alternative to powered escape route lighting. The fact that this is an opinion rather than a definite conclusion is due to the second opinion that while visibility is a necessary condition for fast evacuation of a building, it is not a sufficient condition. There are many other factors such as route capacity, the presence of people of limited mobility and the number of twists and turns along the route that is important to the evacuation of a building. These factors can be present in field trials and may confuse the interpretation of the results. This leads to the third opinion that it is only after the effectiveness of photoluminescent marking using alkali earth aluminate phosphors has been tested under carefully controlled laboratory conditions it will be possible to reach a definite conclusion about its exact merits relative to powered escape route lighting.

9.6 SPECIAL SITUATIONS

So far, this consideration of escape lighting has ignored a number of situations that may make current escape lighting systems inadequate. These situations cover both the physical and the physiological. The main physical situation that is often ignored is the presence of smoke, a situation where escape is often a necessity. The physiological situations include the presence of people with defective colour vision, very limited visual capabilities and limited mobility. Each of these situations will be considered in turn.

9.6.1 Smoke

Watanabe et al. (1973) studied the movement of firemen through smoke. Not surprisingly, movement speed decreased as the density of the smoke increased until speed became constant at a level equal to that measured in complete darkness.

Physically, smoke consists of aerosols suspended in air. Light incident on these particles is both scattered and absorbed. The simplest approach to quantifying the effect of smoke on light is to ignore the distinction between scatter and absorption and treat their combined effect on light loss as absorption alone. In mathematical terms, this approach is expressed in Lambert's law, which states that the luminous intensity, I, of light propagating a distance d through a uniform medium is given by

$$I = I_0 e^{-Ad}$$

where
I_0 is the unattenuated luminous intensity (cd) at distance d (m) equal to zero
A is the absorption coefficient

The effect of applying Lambert's law to an exit sign is to reduce the luminance of all parts of the sign by the same proportion, without any blurring.

Although Lambert's law is simple to apply, it does oversimplify the effects of smoke (Rubini and Zhang, 2007). Scatter is not the same as absorption. Light that is absorbed when it interacts with a particle is eliminated. Light that is scattered when it interacts with a particle is simply moved to another location. Scattered light can be divided into two types: large-angle scatter and small-angle forward scatter. Large-angle scattering can remove light from the field of view, resulting in an overall reduction in luminance. However, in the case of high particle density smoke, multiple, large-angle scattering can cause some of the scattered light to reach the eye resulting in a luminous veil over the entire retinal image. When the object being viewed is the only source of illumination, this luminous veil caused by large-angle scatter is slight because the amount of light reaching the eye is a small fraction of the light that has been scattered equally over all angles. When there are other light sources present, the luminous veil caused by large-angle scattering can be large if the light output of the other sources is large compared with the light output of the object being viewed. This is why the presence of escape route lighting can reduce the visibility of exit signs in smoke.

When the scattering angle is very small, the scattering is described as small-angle forward scatter. Small-angle forward scatter changes the path of the light slightly, but the light usually still reaches the eye. Such forward-scattered light contributes little to light loss but rather degrades the retinal image quality by smoothing out the luminance distribution of the retinal image.

Light loss and retinal image quality are both important for exit sign visibility because light loss reduces average sign luminance and image quality affects the luminance contrast. Schooley and Reagan (1980a,b) examined the effect of smoke on the distance at which the two types of exit sign were visible. The two exit signs were an internally illuminated sign and a self-luminous sign. Both signs conformed to the then requirements of the Life Safety Code. In an unlit room, the distance at which the sign was visible increased as the luminance of the sign increased. This is consistent with the results of Rea et al. (1985b) as well as Collins et al. (1990). Rea et al. (1985b) had participants view 13 different exit signs through a smoke chamber from a fixed distance. The density of the white smoke used was increased in the chamber until the sign reached two threshold criteria: readability (can just read the sign) and detectability (can just detect the presence of something). The 13 signs were representative of exit signs used in Canada at the time and consisted of 4 internally illuminated signs equipped with either incandescent or fluorescent lamps, 3 externally illuminated exit signs lit by incandescent lamps and 2 self-luminous signs. Figure 9.9 shows the critical smoke densities, that is, the smoke density required to bring each sign to the threshold criterion, for each of the 13 signs, plotted against the general luminance of the sign. The smoke density is defined as the optical density of the smoke per metre of path length. Optical density is defined as the logarithm of the reciprocal of the transmittance of the smoke. The general luminance of the sign is the average luminance of a circular area enclosing most of the letters and their immediate background. From Figure 9.9, it can be seen that the higher is the sign's general luminance, the greater is the smoke density through which the sign can be detected and read.

It is also evident from the variation of critical smoke density for different signs in Figure 9.9 that general luminance is not the only important factor. Among other factors likely to be important are the colour format of the sign, the polarity of the contrast and the uniformity of the luminance of the letters. Among the signs used by Rea et al. (1985b) were those with red letters on a white background, red letters on a black background, green letters on a white background, green letters on a black background, green letters on a red background, black letters on a green background and white letters on a red background. There was no consistent effect of colour format on the critical smoke density.

Ouellette (1988) examined the visibility of signs with different polarity of contrast, that is, bright letters on a dark background or dark letters on a bright background. He found that there were small but statistically significant differences in visibility due to contrast polarity. On average, signs with high-luminance backgrounds needed a

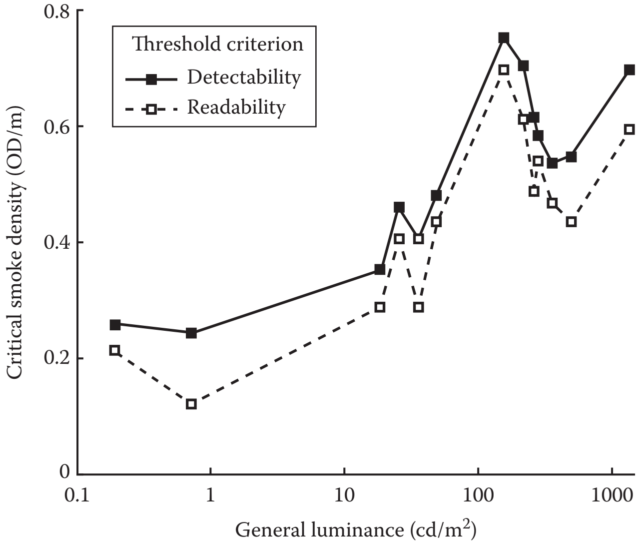


FIGURE 9.9 Smoke density required to make 13 different exit signs just detectable and just readable, plotted against general luminance of the signs. (After Rea, M.S. et al., *Photometric and Psycho-physical Measurements of Exit Signs through Smoke*, National Research Council of Canada, DBR Paper 1291, National Research Council Canada, Ottawa, Ontario, Canada, 1985b.)

higher luminance to be seen through the same density of white smoke compared to those with low-luminance backgrounds. This effect can be explained by the scattering of the light emitted by the sign in the smoke. Light scattered from a high-luminance background will tend to mask the lower-luminance letters on the sign making the sign less visible. Collins et al. (1990) reached a similar conclusion using black smoke. Specifically, stencil signs (transilluminated letters and opaque background) were considered more visible than panel signs (transilluminated letters and background).

As for the effect of uniformity of luminance on visibility, so far this has not been methodically studied. It can be speculated that a very non-uniform luminance sign will be less readable, particularly in smoke, since light scattered from the areas of higher luminance would likely mask the areas of lower luminance and hence fragment the display. This is an aspect of sign design deserving of investigation.

Rea et al. (1985b) also examined the effects of having ambient illumination present in smoke, such as would occur when the normal lighting is on. The ambient illumination on a horizontal plane through the smoke chamber ranged from 170 to 1200 lx. The illuminance falling on the face of the exit signs was 75 lx. Figure 9.10 shows the critical smoke density for readability for the 13 exit signs plotted against the sign general luminance, with the ambient lighting on and off. It is obvious that having the ambient lighting on makes all the signs less visible, although the reduction is of different magnitude for different signs.

Taken together, these studies provide a qualitative specification for conventional exit signs that will ensure they are effective in smoke. Ideally, the sign most easily read through smoke will be large in size, will be of the stencil type and will have a high

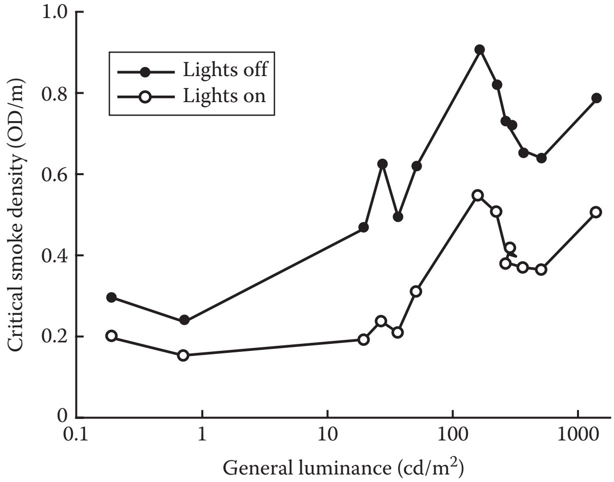


FIGURE 9.10 Smoke density required to make 13 different exit signs just readable, with the ambient lighting on and off, plotted against the general luminance of the signs. When the ambient lighting was on, it provided an illuminance on the face of the sign of 75 lx in the absence of smoke. (After Rea, M.S. et al., *Photometric and Psycho-physical Measurements of Exit Signs through Smoke*, National Research Council of Canada, DBR Paper 1291, National Research Council Canada, Ottawa, Ontario, Canada, 1985b.)

letter luminance. However, there is one important question that needs to be considered: what is the smoke density that people can survive for a brief time? There is little point in making an exit sign visible through smoke that is so dense that anyone present is already dead. Unfortunately, there is no simple answer to this problem because it depends on the associated temperature and the constituents of the smoke. Death in fires can occur in three ways: by thermal collapse, by the inhalation of toxic gases or by the inhalation of irritant gases. Thus, an optical density that may be survivable in one type of smoke may not be survivable in another. Newman and Kahn (1984) suggest that the critical smoke density for short-term exposure is 0.22 m^{-1}, while Gross (1986) and Chittum and Rasmussen (1989) use a just survivable smoke density of 1.64 m^{-1}.

It is interesting to consider the implications of these survivable smoke densities. All the signs examined by Collins et al. (1990) at a distance of 19 m (62 ft) had disappeared in black smoke at smoke densities less than 0.17 m^{-1}. The equation describing the relationship between smoke density, viewing distance and sign luminous intensity is

$$\log\left(\frac{I_0}{I_s}\right) = SD \times d$$

where

I_0 is the luminous intensity of the sign in a clear atmosphere (cd)
I_s is the luminous intensity of the sign in smoke (cd)
SD is the smoke density equal to the optical density per unit path length (m^{-1})
d is the path length (m)

Using this equation, the data from Collins et al. (1990) imply that the value of the logarithm corresponding to the disappearance of all the signs in black smoke is 3.23. For this ratio and a survivable smoke density of 0.22 m^{-1}, the distance at which all the signs examined by Collins et al. (1990) would have disappeared is 14.7 m (50 ft). If the survivable optical density is 1.64 m^{-1}, the distance at which all the signs would have disappeared is 1.97 m (6.5 ft). Finally, a report by the UK Health and Safety Executive (HSE, 1998) suggests that path-marking systems should be tested to ensure visibility of signs and markers at a distance of 3.5 m in smoke of optical density 0.5 m^{-1}, such smoke being survivable for the likely duration of exposure. Despite the uncertainty associated with survivable smoke densities, there can be little doubt that few commercially available exit signs will be visible at 30 m (100 ft) through survivable smoke densities, even in the absence of escape route lighting.

This raises the question of how the visibility of exit signs in smoke might be improved. One way would be to exploit the methodology of Rubini and Zhang (2007) for providing a photorealistic simulation of visibility through a smoke-laden environment. This would enable the effects of many different variables to be examined. However, the results discussed earlier indicate that the most fruitful approach would probably be to increase the luminance of the sign. If the effect of smoke on light was limited to absorption, then increasing the luminance would be all that was required. However, smoke scatters as well as absorbs light, and scattered light will tend to mask the message carried by the sign. Therefore, the highest luminance of the sign should be generated by the part of the sign that carries the message. Gross (1986) describes an exit sign that uses LEDs to form a matrix spelling out the letters of the word 'EXIT'. Gross (1988) claims a marked increase in the distance at which such signs can be read in dense smoke compared to conventional, internally illuminated exit signs.

Rather than attempt to increase the luminance of exit signs sufficiently for them to be seen through a survivable smoke density at 30 m (100 ft), an alternative approach would be to use a low-mounted, path-marking system (see Section 9.5.2). Such systems have two advantages. The first is that any path-marking system provides information at much more frequent intervals than does the conventional exit sign/ceiling-mounted escape route lighting approach, so the need to see information far away through smoke is eliminated. The second is the low-level mounting position. This is valuable because it places the light sources closer to the surface of the escape route and the distribution of smoke is not always uniform. Hot smoke tends to accumulate at the ceiling, initially, and then gradually extend in layers down to the floor. This stratified structure will be evident until the smoke temperature falls or until sprinklers start operating, in which cases smoke will rapidly become evenly distributed throughout the space. A stratified smoke structure means that smoke close to the origin of the fire will be thinnest at floor level so the absorption and scattering of light originating close to the floor should be less. Chesterfield et al. (1981) compared the effectiveness of ceiling-mounted lighting and lighting mounted in armrests for the evacuation of an airliner in smoke. The results obtained showed that the lower-mounted lighting allowed an 18% improvement in evacuation time compared with the ceiling-mounted lighting. Paulsen (1994) examined the time taken for people to cover a route simulating the interior of a ship that involved moving along a corridor, up a flight of stairs, and along another corridor to a door giving access to an open deck. The whole interior was filled with white smoke. The escape lighting that achieved 100% successful evacuation in the shortest time (68 s) was a continuous, incandescent, low-mounted path-marking system with a mean luminance of 5.5 cd/m^2. An escape lighting system based on six exit signs positioned at head height and indicating changes of direction produced a longer evacuation time and allowed only two thirds of the subjects to successfully find their way to the open deck.

Webber and Aizlewood (1993a) had people discover how far they had to be away before they could see the door at the end of a smoke-filled corridor, for five different exit signs, three different path-marking systems and traditional ceiling-mounted escape route lighting. Also, they asked the observers if they would be willing to move along the corridor in smoke with the lighting they had just seen and to rate how satisfactory the lighting was for an emergency smoke condition. The smoke density varied along the length of the corridor, being densest closest to the door, with an average value of about 0.4 m^{-1}. The distribution of smoke was similar for all the lighting conditions. Figure 9.11 shows the distance from the door at which the door was first detected and then when it was confidently recognized. As would be expected from the discussion earlier, the distances increased approximately logarithmically with the luminance of the sign. The distances for the path-marking systems are intermediate in the range of exit signs. Figure 9.12 shows the percentage of

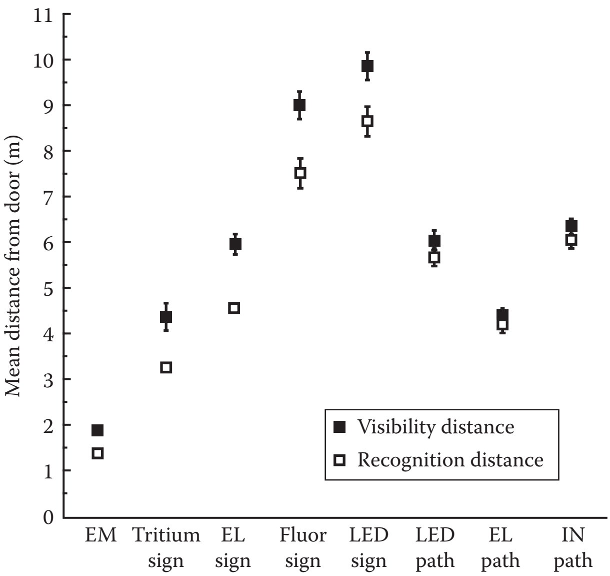


FIGURE 9.11 The mean distance at which a door at the end of a smoke-filled corridor could first be detected and recognized through a smoke density of 0.4/m. The lighting examined was radioluminescent (tritium), electroluminescent (EL), fluorescent (Fluor) or LED exit signs alone; ceiling-mounted escape route lighting luminaires (EM); or incandescent (IN), electroluminescent (EL) or LED path-marking systems. (After Webber, G.M.B. and Aizlewood, C.E., Investigation of emergency wayfinding lighting systems, *Proceedings of Lux Europa 1993*, CIBSE, London, U.K., 1993a.)

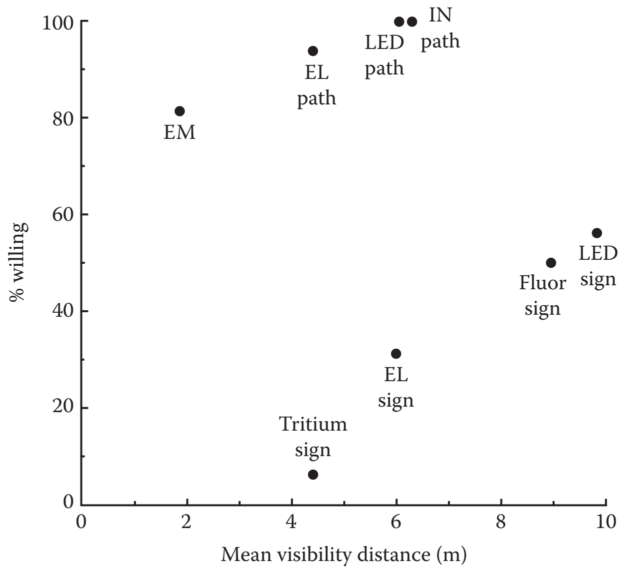


FIGURE 9.12 Percentage of participants willing to start moving down a smoke-filled corridor (smoke density = 0.4/m) when the corridor and the door at the end were lit by radioluminescent (tritium), electroluminescent (EL), fluorescent (Fluor) or LED exit signs alone; ceiling-mounted escape route lighting luminaires (EM); or incandescent (IN), electroluminescent (EL) or LED path-marking systems, plotted against the mean distance at which the exit sign or the door marking could first be detected. (After Webber, G.M.B. and Aizlewood, C.E., Investigation of emergency wayfinding lighting systems, *Proceedings of Lux Europa 1993*, CIBSE, London, U.K., 1993a.)

people willing to start to move along the corridor. Clearly, a much higher percentage of people would be willing to start to move along the corridor when the corridor was lit in some way, either by conventional, ceiling-mounted escape route lighting or by path-marking systems, than would when an exit sign alone was used. Figure 9.13 shows the mean rating of how satisfactory for a smoke emergency condition the various systems were. There can be little doubt that in smoke, the path-marking systems are considered more satisfactory than the ceiling-mounted escape route lighting and that in turn is considered more satisfactory than the exit signs alone.

Webber and Aizlewood (1994) offer another approach to assessing the visibility of various means of providing emergency egress information in smoke. For one observer, they measured the distance at which different components in an escape lighting system, such as exit signs, marked door frames and path marking, could just be seen along a corridor filled with white smoke of various densities. They found that over the range of distances examined, the product of the smoke density and the viewing distance of the observer, that is, the optical density of the smoke, was a constant, although there was a different constant for each component. Table 9.5 gives the mean optical density at which each component was just visible. The larger is the mean optical density, the more visible is the component. Table 9.5 also gives the mean luminance of the letters in the exit signs, the door frame markings and the

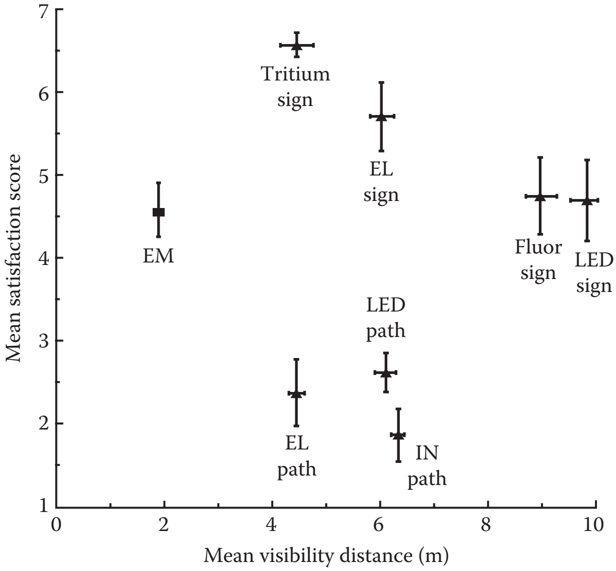


FIGURE 9.13 Mean satisfaction ratings, and the associated standard errors, for the lighting of a corridor and door in an emergency smoke condition, plotted against the mean distance at which the signs or marking identifying the door at the end of the corridor could be recognized through a smoke density of 0.4/m. The satisfaction ratings were given on a seven point scale with 1 = very satisfactory and 7 = very unsatisfactory. The escape route lighting consisted of radioluminescent (tritium), electroluminescent (EL), fluorescent (Fluor) or LED exit signs alone; ceiling-mounted escape route lighting luminaires (EM); or incandescent (IN), electroluminescent (EL) or LED path-marking systems. (After Webber, G.M.B. and Aizlewood, C.E., Investigation of emergency wayfinding lighting systems, *Proceedings of Lux Europa 1993*, CIBSE, London, U.K., 1993a.)

path markings. There is clearly a broad relationship between the luminance of the component and the associated optical density; the higher the luminance, the higher the mean optical density. The mean optical density given in Table 9.5 is valuable because, given that it is constant for a given component, it can be used to predict the smoke density before that component becomes invisible for a fixed viewing distance or, for a constant smoke density, how far away the observer can be before the component disappears. Figure 9.14 is derived from the smoke densities for a range of exit signs and a number of door frame markings using the same materials as the path marking. It is clear from Figure 9.14 that any smoke density above about 0.5 m^{-1} severely restricts the distance at which any of these components are visible. This strong obscuring effect of smoke suggests that a well-planned path-marking system, that provides information on the direction to go at closely spaced intervals, will be a better choice for escape route lighting where the presence of dense but survivable smoke is considered a possibility.

Webber et al. (2001) examined the effect of smoke in another way by measuring the speed of movement over a route lit by normal lighting, ceiling-mounted escape route lighting and four different forms of powered path-marking systems using

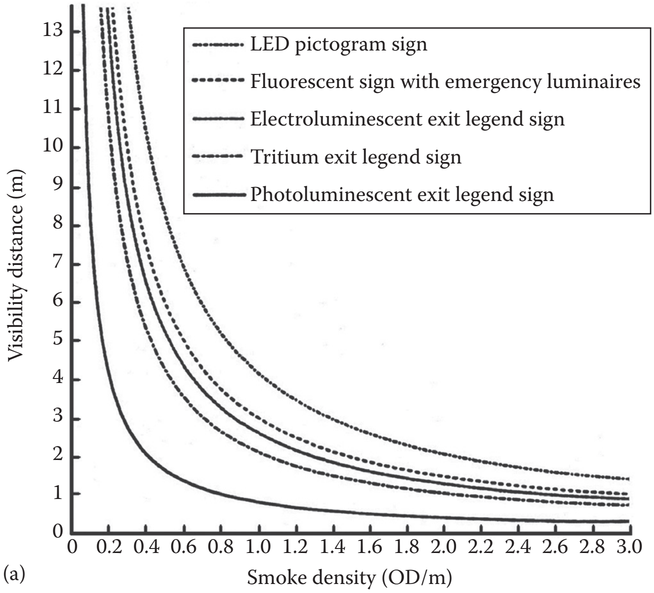
TABLE 9.5
Mean Optical Density of Smoke When Various Components of Escape Lighting Systems Were Just Visible and the Mean Luminance of That Component

Component	Mean Optical Density	Component Luminance (cd/m²)
Photoluminescent exit sign after 1 min	0.84	0.042
Photoluminescent door frame marking after 1 min	1.60	0.042
Radioluminescent door frame marking	1.65	0.61
Radioluminescent exit sign	2.13	0.51
Electroluminescent exit sign	2.61	0.33
Electroluminescent door frame marking	2.61	7.32
Ceiling-mounted escape route lighting and a fluorescent pictogram sign	3.00	935
LED door frame marking	3.01	562
Fluorescent pictogram exit sign	3.19	935
Miniature incandescent door frame marking	3.23	1610
Low-mounted LED exit sign	3.60	1890
LED exit sign	4.01	3280
LED pictogram exit sign	4.15	2320

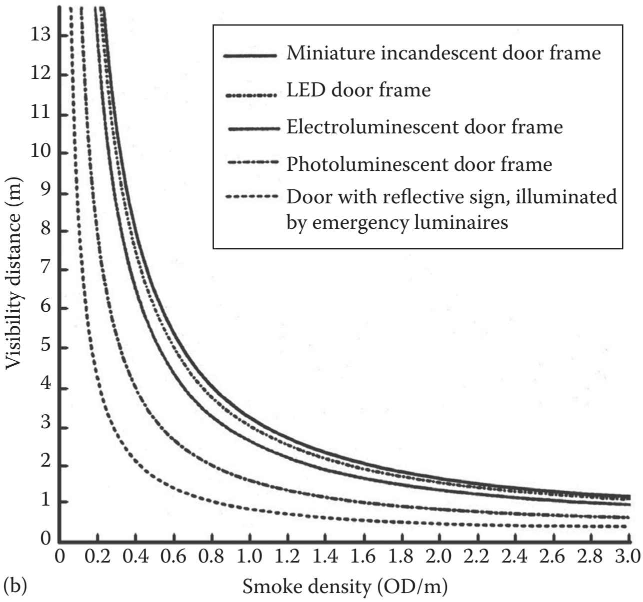
Source: After Webber, G.M.B. and Aizlewood, C.E., Emergency lighting and wayfinding systems in smoke, *Proceedings of the CIBSE National Lighting Conference*, Cambridge, CIBSE, London, U.K., 1994.

electroluminescent, LED and incandescent light sources. Figure 9.15 shows the mean speeds of 18 people moving along a 13 m corridor filled with white smoke to an average optical density of 1.1 m^{-1} and down a staircase filled with white smoke to an average optical density of 1.2 m^{-1} plotted against the illuminance provided on the route. From Figure 9.15, it is clear that walking speeds in smoke are slower under ceiling-mounted lighting than for powered path-marking systems, for both corridor and stair. Further, for both ceiling-mounted lighting and powered path-marking systems, the walking speeds in smoke are slower than those measured in the same facility without smoke (cf. Figure 9.15 with Figures 9.7 and 9.8). It is also worth noting that providing much more light from the ceiling is of little benefit when smoke is present.

While there can be little doubt that frequent path marking located close to the floor is more effective in guiding people along an escape route in smoke than conventional, ceiling-mounted escape route lighting, it is important to remember why conventional escape route lighting and exit signs are mounted above head height. The reason is to reduce the likelihood of the route marking being obstructed by people, furniture and equipment. This implies that the low-level escape route marking is, as its name implies, strictly of value for marking defined escape routes which are kept clear of obstructions. This leaves open the question of what is the best way to guide people from an obstructed occupied space to the escape route when smoke is present.



(a)



(b)

FIGURE 9.14 Models of the distance at which (a) exit signs of various types and (b) door markings of various types can be seen through different smoke densities. (After Webber, G.M.B. and Aizlewood, C.E., Emergency lighting and wayfinding systems in smoke, *Proceedings of the CIBSE National Lighting Conference, Cambridge*, CIBSE, London, U.K., 1994.)

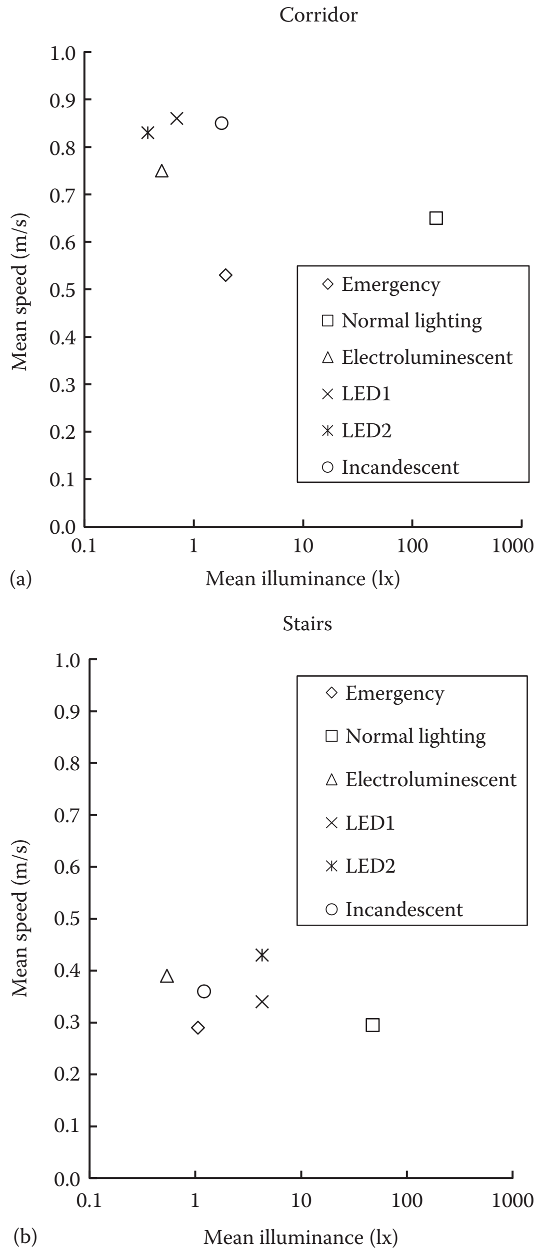


FIGURE 9.15 Mean walking speed for movement along (a) a corridor and (b) down a flight of stairs filled with white smoke plotted against the mean illuminance on the floor of the route. The corridor and stairs were lit with either normal ceiling-mounted lighting, ceiling-mounted emergency lighting or four forms of powered path-marking system. (After Webber, G.M.B. et al., The effects of smoke on people's walking speeds using overhead lighting and wayguidance provision, *Human Behaviour in Fires, Proceedings of the 2nd International Conference*, Interscience Communications, Greenwich, U.K., 2001.)

One complicating aspect of visibility in smoke that has not been studied in the experiments discussed earlier is the effect of the smoke on the eye. Jin (1978) measured the distance at which an exit sign could be read by people walking down a corridor in the presence of irritant and non-irritant smoke of a known density. The results showed that the irritant smoke reduced the visibility distance markedly because the subjects' eyes watered profusely. Jin (1978) also examined peoples' walking speeds through both irritant and non-irritant smoke. Walking speeds were much reduced in irritant smoke, and providing more light was ineffective.

9.6.2 People with Defective Colour Vision

Given that colour is an intrinsic component in exit signs and is important for the identification of a sign as an exit sign, it seems reasonable to ask how effective various colours of exit sign would be in conveying information to individuals with defective colour vision. Eklund (1999) examined this question, using people with normal colour vision and deutan and protan observers (see Section 2.2.7 for a description of the various forms of defective colour vision). The apparatus used provided independent control of the letter and background colours and luminances for the word 'EXIT'. The word 'EXIT' could appear normal or reversed and was sized to correspond to an exit sign conforming to the Life Safety Code seen from 30 m (100 ft). LEDs, with different peak wavelengths, were used to provide the light for the letters and background of the exit sign. The observer's task was simply to recognize the orientation of the sign. Because there are only two possible orientations, the recognition performance for the orientation of the exit sign can range from 100% to 50%, the latter being achieved by guessing. Figure 9.16 shows the recognition performance for colour normal, deutan and protan observers, for green (peak wavelength = 530 nm) and red (peak wavelength = 660 nm) letters seen against a white background, plotted against luminance contrast. The results in Figure 9.16 show that the only condition in which recognition performance is much reduced is for the green letters on the white background, seen by protans. This result raises an interesting question. Why is the recognition performance of protans good with the red letters and relatively bad with the green letters? Eklund (1999) suggests that the explanation lies in the spectral sensitivity of the protans' visual system. Specifically, protans do not have long-wavelength-sensitive cones and consequently have a reduced sensitivity in the long-wavelength region of the visible spectrum. This alters the luminance contrast provided by the sign for protans. Figure 9.17 gives estimates of the protan equivalent luminance (PEL) contrast matched to the luminance contrast for people with normal colour vision based on the spectral sensitivity curve for protanomalous and normal colour vision observers (Wyszecki and Stiles, 1982). From Figure 9.17, it can be seen that for the red LEDs, the PEL contrast is highly negative over the range of luminance contrasts examined (−0.5 to +0.5), that is, the red letters on a white background appear to the protans as black on white. For the green LEDs, the PEL contrast is low for the luminance contrasts that are low, with a slight bias towards the negative, which explains the pattern of recognition performance in Figure 9.16.

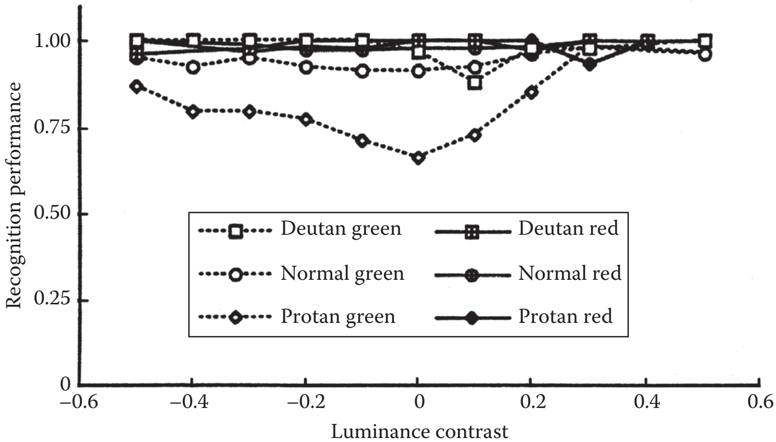


FIGURE 9.16 Recognition performance expressed as the proportion of correct identifications of the orientation of an exit sign, plotted against negative and positive luminance contrast, for colour normal, deutan and protan participants. The two types of exit signs use green LEDs (peak wavelength = 530 nm) or red LEDs (peak wavelength = 660 nm) against a white background. (After Eklund, N.H., *J. Illum. Eng. Soc.*, 28, 71, 1999.)

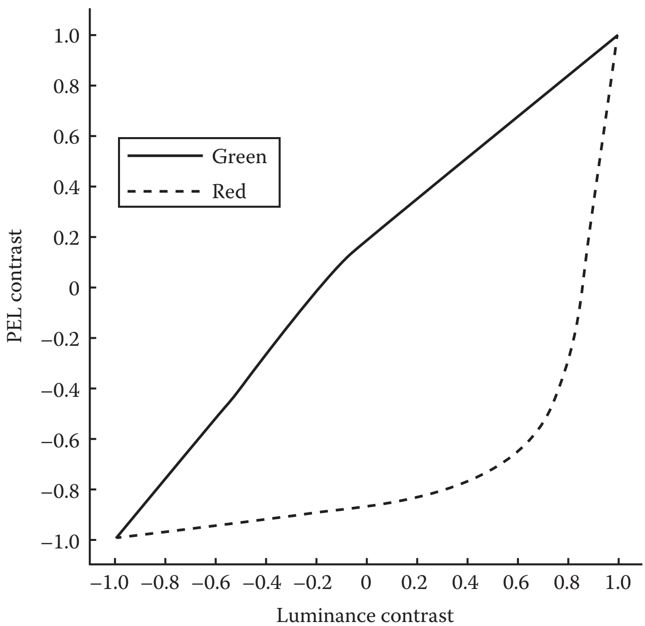


FIGURE 9.17 PEL contrast plotted against luminance contrast, for green and red LED signals. The peak wavelengths for the LEDs are green = 530 nm and red = 660 nm. (After Eklund, N.H., *J. Illum. Eng. Soc.*, 28, 71, 1999.)

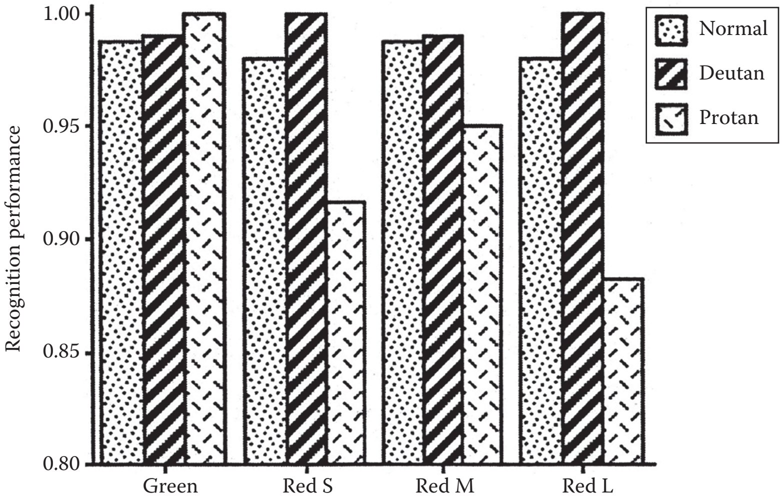


FIGURE 9.18 Recognition performance expressed as the proportion of correct identifications of the orientation of an exit sign for signs using green and red LEDs, by colour normal, deutan and protan participants, on a dark background. The peak wavelengths for the LEDs are green = 530 nm, red S = 622 nm, red M = 632 nm and red L = 660 nm. (After Eklund, N.H., *J. Illum. Eng. Soc.*, 28, 71, 1999.)

These results are applicable to panel exit signs, where both letters and background have luminances above zero, even in the no-power condition. But what happens when a stencil sign is used, so that in the no-power condition, the background luminance is zero and the luminance contrast is very high? Figure 9.18 answers this question. It shows the recognition performance for colour normals, deutans and protans for the four different LED colours. In this condition, protans show worse recognition performance than colour normals or deutans for the red LEDs but not for the green LED. Again, the worse recognition performance for the red LEDs by the protans can be explained by the reduced sensitivity of protans at long wavelengths. The reduced sensitivity means the equivalent luminance of the red letters is less for protans, which, when combined with the black background, leads to a lower PEL contrast signal.

Two conclusions and one implication can be drawn from these results. The first conclusion is that what matters for recognition performance is the contrast between the letters of the sign and the background. The second conclusion is conditions that may be very good for colour normals may be poor for colour defectives. For example, Figure 9.17 suggests that luminance contrasts in the range +0.6 to +0.8, which would ensure a high level of recognition performance for colour normals, would lead to poor recognition performance by protans for red letters on a white background. The implication is that the most effective exit sign for colour normals and for deutans and protans is a green stencil sign, that is, green letters on a dark background. This format provides a high level of recognition performance regardless of ambient illumination (see Figures 9.16 and 9.18). This, at least, is a rational reason for choosing between exit sign colours.

9.6.3 People with Low Vision

All the studies discussed above have used people with normal visual acuities and visual field sizes. However, buildings are also used by people with limited visual capabilities. Age is by far the most common cause of limited visual capability. By the fourth decade of life, most people experience limits on focusing distance; by the sixth decade, the prevalence of pathological conditions in the optic media of the eye starts to increase; and by the seventh decade, the prevalence of pathological conditions in the retina increases rapidly (see Chapter 13). These changes reduce the ability to resolve detail, to discriminate colours and to adapt to a sudden change in illumination and increase sensitivity to glare. Many of these changes can be expected to influence how people with limited visual capabilities can use the information provided by escape lighting.

Pasini and Proulx (1988) studied the manner in which people with low vision moved through a building under normal conditions. They concluded that the visually impaired navigate through a building by wayfaring, that is, by making a series of decisions at frequent intervals. They suggest that people with low vision would benefit from regularly spaced information that is easily perceived and has a distinctive identity when attempting to move around a building under normal conditions. This implies that the path-marking approach discussed above, particularly if it could also have some tactile characteristic, would be of use to people with low vision seeking to leave a building under emergency conditions. The Life Safety Code (NFPA, 2012) does now require exit doors in new buildings to be marked by a tactile sign spelling out the word EXIT.

Wright et al. (1999) report a study in which groups of 30 people with different forms of low vision were asked to move over an escape route, involving both a corridor and some stairs. A comparison group of people with normal vision was also used. The escape route was lit by different combinations of ceiling-mounted lighting and path marking. Measurements of speed of movement showed that the walking speeds of low vision group on the escape route was generally about 45%–70% that of normally sighted people in the corridor and about 75%–80% on the stairs. Figure 9.19 shows the movement speeds of the low-vision group in the corridor and on the stairs, plotted against the mean illuminance provided on the escape route, including that provided by the normal lighting. As would be expected, the higher is the illuminance, the faster is the speed of movement. Figure 9.20 shows the mean ratings of how difficult it was to see where to go plotted against the mean illuminance. Again, the mean rating shows a steady improvement with increasing illuminance. As for the different systems, the photoluminescent path-marking system produces both the slowest movement speed and the ratings of greatest difficulty; the ceiling-mounted escape lighting is worse than the powered path-marking systems at similar illuminances; and the normal lighting provides the fastest speed and least difficulty of all. Cook et al. (1999) did a similar study, with similar results, although increasing the mean illuminance provided on the escape route by the ceiling-mounted system from about 1.9 lx to about 6.4 lx gave the ceiling-mounted system the lowest difficulty rating. This, again, emphasizes that, in the absence of smoke, the important factor is not the particular technology used, nor the location of the lighting, but rather the amount of light produced on the escape route.

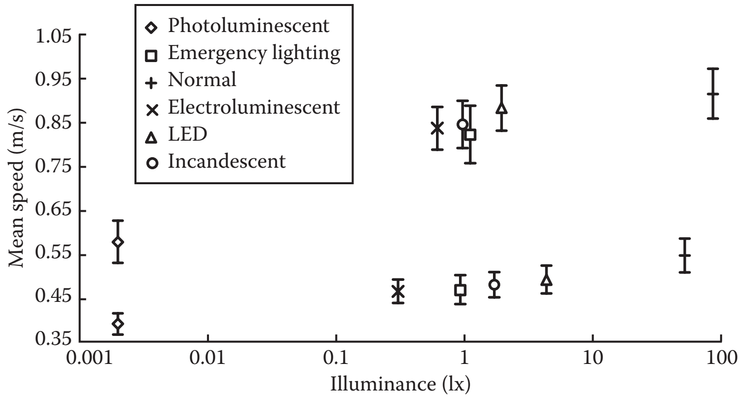


FIGURE 9.19 Mean speed of movement (and the standard error of the mean) of people with low vision down a stair and along a corridor plotted against the mean illuminance (lx) on the escape route. The upper, faster, set of speeds is for the corridor. The lower, slower, set of speeds is for the stairs. The escape route lighting consists of a photoluminescent path-marking system, normal ceiling-mounted lighting providing 70 lx on the floor, a LED path-marking system, a ceiling-mounted emergency lighting system, an electroluminescent path-marking system and a miniature incandescent path-marking system. The 30 low-vision subjects included nine with retinitis pigmentosa, eight with macular degeneration, four with cataract, three with glaucoma, two with diabetic retinopathy and four with other causes of vision loss. (After Wright, M.S. et al., *Lighting Res. Technol.*, 31, 35, 1999.)

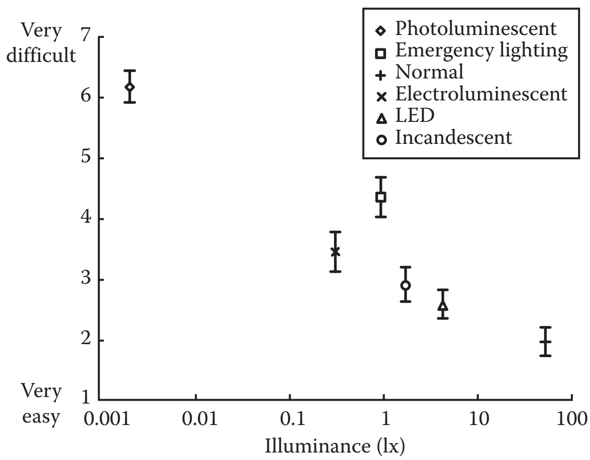


FIGURE 9.20 Mean ratings of difficulty of seeing where to go (and the standard error of the mean) given by people with low vision moving down a stair and along a corridor plotted against the mean illuminance (lx) on the escape route. The escape route lighting consists of a photoluminescent path-marking system, normal ceiling-mounted lighting providing 70 lx on the floor, a LED path-marking system, a ceiling-mounted emergency lighting system, an electroluminescent path-marking system and a miniature incandescent path-marking system. The 30 low-vision subjects included nine with retinitis pigmentosa, eight with macular degeneration, four with cataract, three with glaucoma, two with diabetic retinopathy and four with other causes of vision loss. (After Wright, M.S. et al., *Lighting Res. Technol.*, 31, 35, 1999.).

9.6.4 People with Limited Mobility

Another special situation deserving consideration is an emergency requiring evacuation in a building where there are people of limited mobility. Typical buildings would be hospitals and nursing homes. Studies of the ease of evacuation of such buildings have been made (see Canter, 1980), but the role of emergency egress information is not mentioned. This is probably because people of limited mobility need assistance to move over the escape route, and it is assumed that the helpers will have normal visual capabilities. This is a reasonable assumption, but what it implies is that evacuation times will be much longer than for a normally mobile population. In this circumstance, the emergency egress information may need to be available for a much longer time period than is usually specified in the event of a power failure.

9.7 ESCAPE LIGHTING IN PRACTICE

The research discussed above has been concerned primarily with the specification of escape lighting. While this is important, it is also necessary to consider how well any specification is implemented in practice. Ouellette et al. (1993) carried out a careful evaluation of the escape lighting systems in seven, large, 20–30-year-old office buildings in Canada. The escape lighting systems in six of the buildings used conventional luminaires connected to a central generator that started when power failed. The other building used wall-mounted, incandescent floodlights powered by local rechargeable batteries. A visual inspection of the escape lighting in these buildings resulted in some disturbing findings. In many open-plan areas, discrepancies were found between the locations of the escape lighting and the defined escape routes. Often, the lighting of escape routes was shaded by high cubicle dividers. These failings are probably due to changes in the layout of office furniture, without changing the escape routes or the escape lighting. Given the churn rate in office buildings today, it is likely that this is a common situation. To make matters worse, exit signs were not always consistent with escape routes. In the worse cases, exit signs led to locked doors or cul-de-sacs. Measurements of illuminance were made on a horizontal plane, 1 m above floor level, at 1 m intervals along the centre line of escape routes. These measurements revealed a very wide range of values along the escape route. Maximum illuminances in every building were more than 100 lx, and the minimums were all less than 0.4 lx, many being less than 0.1 lx, the minimum measurable with the illuminance meter used. The picture that emerges from these measurements is one of pools of light separated by areas of darkness. The authors comment that ‘in some office areas, especially at night, it would be difficult for people to find their way to safety with the emergency lighting systems now in place’.

Given that similar situations occur in other cities and countries, and there is no reason to suspect that they do not, the question that needs to be addressed is how to improve this situation. The regulatory approach is more frequent inspection of emergency egress systems, including operation of all parts of the system. The Life Safety Code (NFPA, 2012) calls for testing of emergency lighting equipment for function every 30 days, each test to last 30 s and for a test lasting 90 min, annually. SLL (2006a) also calls for regular monthly and annual inspections. In order to be effective, such inspections need not only to observe whether the escape lighting comes on but also to measure the illuminances provided on the escape route. The illuminance measurements made by Ouellette et al. (1993) form a multi-modal distribution. Given such a distribution, mean illuminance is likely to be misleading, particularly if the number of measurement points is limited. Ouellette et al. (1993) recommend that inspectors should look for the dimmest location on the escape route and measure the illuminance there, that is, measure the minimum illuminance on the escape route. They support a minimum illuminance of 0.5 lx. This procedure has the advantage of being simple and quick, but a measurement is of little use unless there is a specification to compare it with. Fortunately, both the Life Safety Code (NFPA, 2012) and other guidance documents (SLL, 2006a; BSI, 2011b) include minimum illuminance specifications for the lighting of escape routes. Another possibility to enhance the quality of escape lighting in practice is to supplement powered exit signs and escape route lighting with photoluminescent path marking and exit signs. These will operate even when the generator refuses to start or the battery in the exit sign is flat. They can also be easily moved when the furniture is rearranged. Of course, no matter how reliable escape lighting is, it will not be effective if it does not match the actual escape route and sends people into a dead end, literally. For this to be avoided, it is important to check the match of the escape lighting to the escape route whenever the system is being inspected.

9.8 SUMMARY

The provision of some means of escape from a building is part of the legal framework of most countries. This provision usually involves defined escape routes and a means of telling the occupants when to leave. Lighting designed to tell occupants which way to go and to illuminate the escape route so that people can move quickly and safely along it when electrical power is absent and/or smoke is present is an important component of emergency egress systems.

Informing occupants where to go to escape from the building is the role of the exit sign. These signs can consist of words or pictograms. In either case, the specification of the exit sign is based on the need for the sign to be visible and conspicuous at a specified distance. The specifications for exit signs usually define the minimum size of the elements of the sign, their luminances and luminance uniformity and the luminance contrast between elements carrying the message and the background. Exit signs of different colours are used in different parts of the world. The value of having an exit sign of colour is that it enhances the conspicuity of the sign relative to other nominally white luminaires that may be operating at the same time. Measurements of exit sign recognition by colour-normal and colour-defective individuals suggest that green, luminous letters or symbols on a black, opaque background are the most effective colour and format for an exit sign. This stencil sign format will also be more effective in smoke than other formats, although very few commercially available exit signs will be visible at the maximum distance in a survivable smoke density.

The other part of an escape lighting system is the lighting of the escape route. This can be provided either by specially powered ceiling- or wall-mounted luminaires or some form of low-mounted path-marking system, either powered or photoluminescent.

There is little to choose between these systems in clear atmospheres, particularly now that brighter photoluminescent systems based on alkali earth aluminate phosphors are available. How fast people can move over the escape route and how often they make contact with obstacles depend on the illuminance produced on the escape route. A minimum illuminance of about 0.5 lx is sufficient to ensure that people will be able to avoid obstacles. Higher illuminances allow for faster movement speeds following a compressive function. As for the light spectrum, there is some evidence that a light spectrum that effectively stimulates rod photoreceptors is advantageous for use on escape routes. Where a difference between the systems does emerge is in smoke. In smoke, the low-mounted path-marking systems are more effective in facilitating movement along an escape route than the wall- or ceiling-mounted systems, provided the path-marking system has sufficient light output to provide an illuminance on the escape route of at least 0.1 lx.

While what is needed to provide good quality escape lighting is fairly well understood, what is offered in practice often falls far short. This is for two reasons. The first is the shameful willingness of some of the organizations responsible for the escape lighting recommendations to pretend that while smoke can occur in buildings, it has no impact on the effectiveness of escape route lighting. This means that escape route lighting meeting many of the legal requirements will not be effective in the one situation where rapid escape is essential. The second is that many escape lighting systems are poorly maintained and/or not modified when the interior of the building is changed. This is because there is a widespread reluctance to provide the resources to enforce the legal requirements relating to escape lighting. In many ways, current escape lighting practice provides a false sense of security.

10 Lighting for Driving

10.1 INTRODUCTION

Driving is a visual task. In terms of the visual, cognitive and motor components of tasks discussed in Section 4.2, the driver's task is to extract information from the environment, to determine what changes in behaviour are necessary and to manoeuvre the vehicle appropriately. Many different aspects of vision are important to driving. Visual acuity, widely used to assess suitability to drive, is only weakly related to driver performance. More significant are contrast sensitivity, visual field size and speed of processing visual information (Owsley and McGwin Jr., 2010). While vision is a necessary condition for being able to drive, alone it is not sufficient. The quality of driving is also influenced by cognitive skills such as learning, remembering and decision-making largely derived from experience and personality variables such as the threshold for boredom and levels of risk aversion. Further, when driving, we receive information through sensors other than vision. When in motion, we receive auditory information from the noise of the vehicle itself and from the environment through which it moves, as well as information about the forces acting on the body obtained from the kinesthetic and vestibular mechanisms.

Despite this multisense input, there can be little doubt that vision is the primary sensory input for driving. The role of lighting in driving is to enable the transfer of visual information, either directly or indirectly. Direct transfer of information occurs when the light source itself conveys the information, for example, a flashing turn lamp on a vehicle or a traffic light. Indirect transfer of information occurs when the light is used to illuminate a surface that is then searched by the driver for whatever information it contains. Such surfaces may be empty but need to be searched for content, for example, a road surface, or they may contain displayed information, as does a road sign. During daytime, there is little problem with vision for driving, apart from the black hole effect that can occur when approaching a tunnel (Boyce, 2009), but at night, it is a different matter. For many miles of road, the only source of illumination is what the driver has on the vehicle. Even when road lighting is provided, this can be very variable in both quantity and quality. This chapter seeks to examine how effective current practices in vehicle lighting and road lighting are in promoting road safety and driver comfort.

10.2 VEHICLE FORWARD LIGHTING

Vehicle lighting can be conveniently divided into two types: lighting designed to enable the driver to see after dark and lighting designed primarily to indicate the presence or give information about the movement of a vehicle. The former category, known as forward lighting, includes headlamps and fog lamps. The latter category, known as signal lighting, includes front and rear position lamps, side marker lamps, stop lamps, turn lamps, daytime running lamps and emergency flashing lamps. One exception to this crude classification is reversing lamps. Reversing lamps provide both visibility to the rear and a signal to others around the vehicle about the direction of movement.

10.2.1 Technology

The most common form of vehicle forward lighting is the headlamp. Headlamp design requires consideration of both the light source and the type of optical control. To be suitable for vehicle forward lighting, light sources have to have sufficient light output to meet the legal requirements that specify the minimum luminous intensities of a headlamp. They also have to meet the customer's expectations about the amount of light immediately available on switch-on. Further, they have to be capable of operating reliably in a wide range of climates as well as withstanding vibration and to last as long as the vehicle. Headlamps in modern vehicles use either tungsten halogen or xenon discharge (HID) light sources, although the light-emitting diode (LED) is poised to make an entrance (Sivak et al., 2004). These light sources differ in their light spectrum, luminous efficacy and life (see Section 1.7). All are used for the conventional lighting of buildings, but when used in vehicles, they are modified to be able to withstand the rigours of the vehicle environment. The main modification for the tungsten halogen light source is to increase the strength of the filament assembly. For the HID light source, the main modification is the addition of xenon to the metal halide (MH) discharge so as to make a significant amount of light available immediately on switch-on and to make the run-up time to full light output much shorter. For the LED headlamp, multiple LEDs are required to generate enough light output and care has to be taken with cooling, particularly for use in hot climates.

Three systems of optical control are used in headlamps to produce the desired luminous intensity distribution, based on reflection, projection and multiple light sources. For the reflector system, the light distribution is determined by the position of the light source relative to the reflector, the shape of the reflector and any optical patterning of the front cover glass. Headlamps using projection have at least three components: a light source, a near ellipsoidal reflector and a condensing lens. Because the reflector is nearly ellipsoidal, it has two foci. The light source is placed at one focus so the reflector produces an image of the source at the second focus. The light distribution after the second focus is strongly divergent, so a condensing lens is used to collimate the beam. Projector headlamps typically use HID light sources. LED headlamps can create the desired light distribution by means of reflectors or lenses together with switching or dimming of individual LEDs.

10.2.2 Regulation

Headlamp luminous intensities, light distribution and placement on the vehicle are all closely regulated. The purpose of these regulations is to bring some order to the potential conflict between drivers caused by the fact that headlamps increase the visual capabilities of the driver sitting behind them but simultaneously decrease the visual capabilities of the driver facing them. These regulations can take different forms in different countries, but the vast majority follows either the recommendations of the US Federal Motor Vehicle Safety Standard (FMVSS) 108 or the

Economic Commission for Europe (ECE). Both sets of recommendations insist that the headlamps fitted to a vehicle have to produce two different luminous intensity distributions, called high beam and low beam. High-beam headlamps are for use when there is no other vehicle on the road ahead so there is no need to limit glare. Low-beam headlamps are for use when there is an approaching vehicle or a vehicle immediately in front. These regulations also demand that the colour appearance of the light emitted by headlamps must be white, defined as emitting light with chromaticity coordinates that fall within a specified region of the Commission Internationale de l'Eclairage (CIE) 1931 chromaticity diagram.

As a result of these regulations, high- and low-beam headlights produce different illuminances at different locations on the road ahead. Figure 10.1 shows contours of the median vertical illuminance for pairs of headlamps used on the 20 best-selling

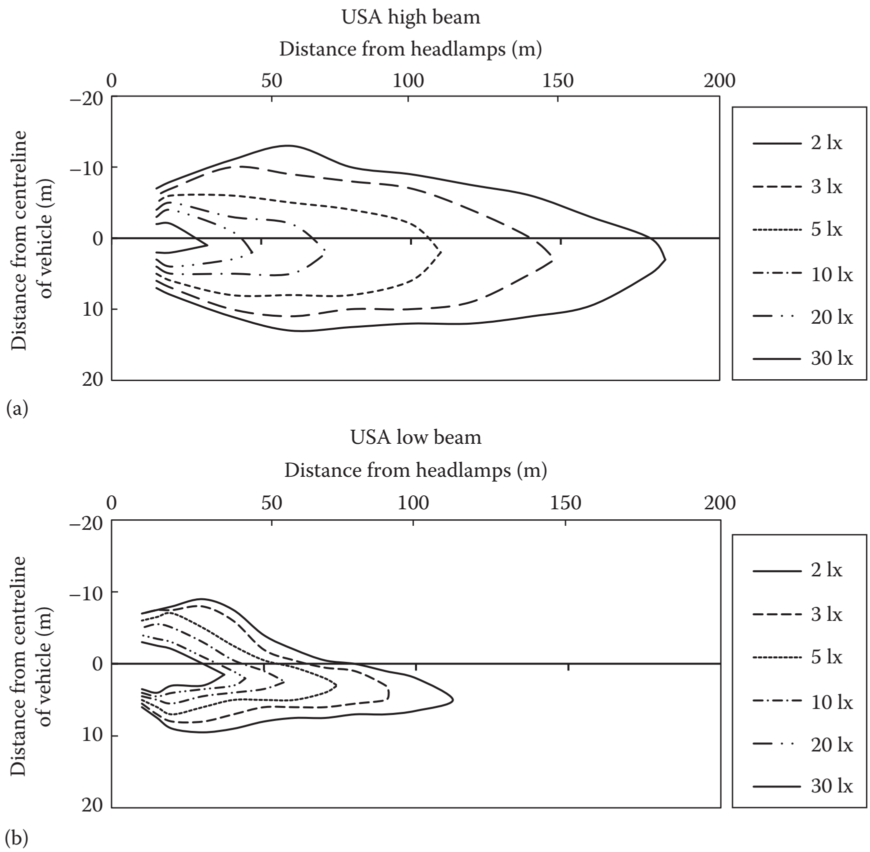


FIGURE 10.1 Contours of median vertical illuminances (lx) produced by pairs of halogen headlamps operating on (a) high beam and (b) low beam for the 20 best-selling passenger vehicles in the United States in the 2000 model year. The vertical illuminances were calculated at road level. Vehicles in the United States are driven on the right. (After Schoettle, B. et al., *High-Beam and Low-Beam Headlighting Patterns in the US and Europe at the Turn of the Millenium*, SAE Paper 2002-01-0262, Society of Automotive Engineers, Warrendale, PA, 2002.)

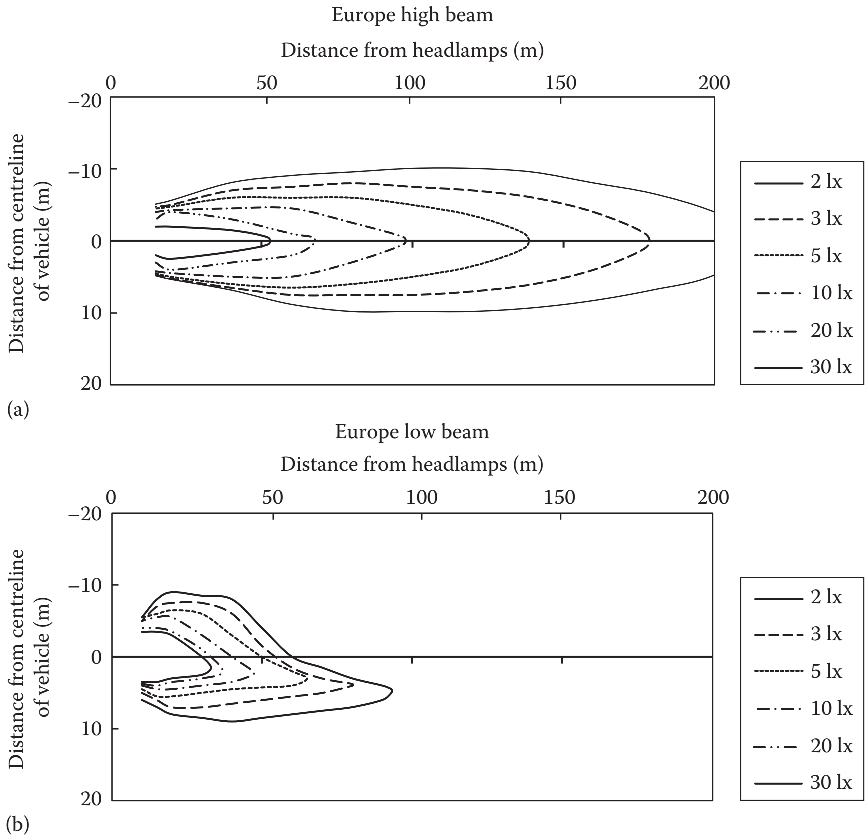


FIGURE 10.2 Contours of median vertical illuminances (lx) produced by pairs of halogen headlamps operating on (a) high beam and (b) low beam for the 20 best-selling passenger vehicles in Europe in the 1999 model year. The vertical illuminances were calculated at road level. Vehicles in most countries of Europe are driven on the right. (After Schoettle, B. et al., *High-Beam and Low-Beam Headlighting Patterns in the US and Europe at the Turn of the Millenium*, SAE Paper 2002-01-0262, Society of Automotive Engineers, Warrendale, PA, 2002.)

passenger vehicles in the United States for the 2000 model year, measured at road level for both low and high beams (Schoettle et al., 2002). Figure 10.2 shows the same measure for pairs of headlamps used on the 20 best-selling passenger vehicles in Europe for the 1999 model year (Schoettle et al., 2002). A comparison of Figures 10.1 and 10.2 reveals some similarities and some differences between the American and European standards. Specifically, the European high beam is narrower and provides more light further down the road than does the American high beam. For low beams, both American and European regulations are similar in that they show an emphasis to the nearside of the road and a limitation of the vertical illuminance produced towards vehicles in the opposing lane. However, the European low beam has a sharper cut-off than the American low beam, indicating the greater emphasis given to controlling disability glare. Conversely, the American low beam provides more light down the road and more on the edge of the road, indicating a greater emphasis on visibility.

10.2.3 Headlamps in Practice

The process of determining whether or not a headlamp design meets the relevant regulations involves careful measurements of a new headlamp taken in a laboratory under very specific conditions. However, headlamps in a vehicle on the road may produce different luminous intensities in important directions for a number of reasons. Some are transient and inherent in the road layout or the nature of the vehicle. An example of the former is the reduction in illumination of the road ahead and the increase in glare to opposing drivers that occur when breasting a hill. An example of the latter is the reduction in the illumination of the road ahead and the increase in glare to opposing drivers produced by motorcycles when cornering to the right on right-hand drive roads due to the tilting of the machine (Konyukhov et al., 2006). Others can be long lasting and occur because the vehicle is not level or the headlamp is incorrectly aimed or dirty. Yerrel (1976) reported a set of roadside measurements of headlamp luminous intensities in Europe and found a very large range of luminous intensities for the same direction despite a common standard. Alferdinck and Padmos (1988) found similar results from roadside measurements in the Netherlands. They also examined the importance of aiming, dirt and lamp age on the luminous intensity in a series of laboratory measurements. Figure 10.3 shows the cumulative frequency distributions of luminous intensity in a direction important for forward visibility and in a direction important for glare to an oncoming driver, for 50 cars taken from a car park. Luminous intensity measurements of the headlamps, as found, but taken in the laboratory, agreed with measurements taken at the roadside. From Figure 10.3, it can be seen that the headlamps, as found, tend to produce less forward visibility and more glare than new headlamps. The forward visibility is most improved by correcting the aiming. Cleaning the headlamps and operating them at 12 V increases the luminous intensity for forward visibility a little and brings it closer to that of new headlamps. For the direction important for glare, correcting the aiming makes things slightly worse, but cleaning the headlamps reduces the luminous intensity causing glare and again brings it close to that of new headlamps. The ranges of luminous intensities shown in Figure 10.3 suggest that fine differences between the recommended headlamp luminous intensity distributions used in America and by countries following the ECE recommendations are trivial compared to the differences that occur in practice.

The range of luminous intensities evident in Figure 10.3 also implies that even when headlamps are correctly aimed, new and clean, there will be a wide variation in how effective they are. This variation is evident from the measurements that have been made of the distances at which targets can be detected when driving on low beams on an unlit road. Perel et al. (1983) reviewed 19 studies in which observers had been driven along an unlit road at a constant speed in vehicles equipped with standard FMVSS or ECE headlamps. The observers were asked to press a button when they detected small (typically 0.5 m^2) or large (man sized), low-reflectance, low-contrast targets placed at the edge of the road. The mean detection distances for the large target ranged from 51 to 122 m, while for the small target, the mean detection distances ranged from 45 to 100 m. It is likely that these detection distances are overestimates of reality because the observers were told to look for the

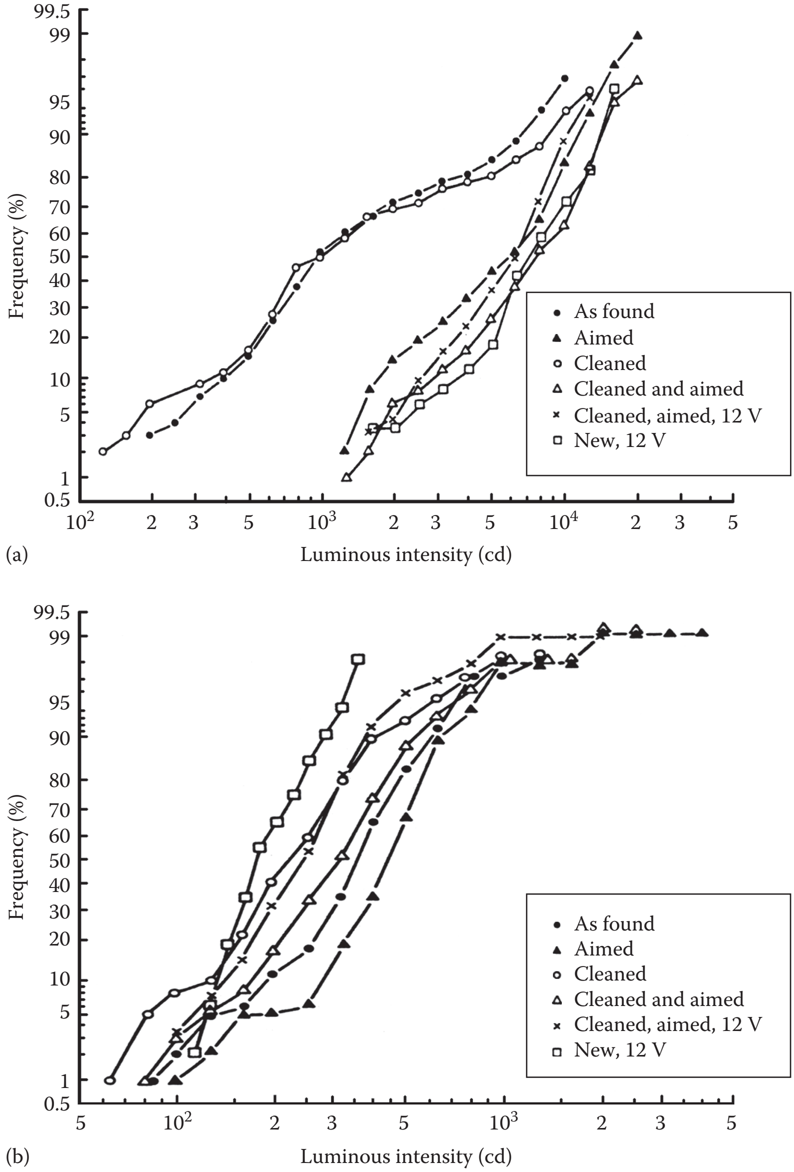


FIGURE 10.3 Cumulative frequency distributions of luminous intensities (cd) in directions (a) important for visibility of the nearside of the road and (b) important for glare to oncoming drivers, for headlamps on 50 cars as found, aimed, cleaned, cleaned and aimed and cleaned, aimed and operated at 12 V and for new headlamps. (After Alferdinck, J.W.A.M. and Padmos, P., *Lighting Res. Technol.*, 20, 195, 1988.)

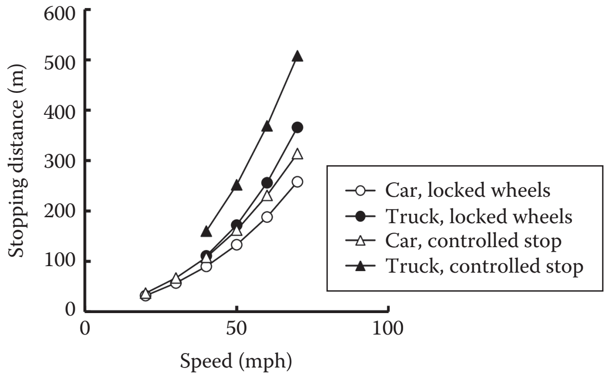


FIGURE 10.4 Stopping distances (m) for cars and trucks with worn tyres making an emergency stop on a wet road surface, with and without locked wheels, plotted against speed (mph) and assuming a driver reaction time of 2.5 s. (After Olson, P.L. et al., *Parameters Affecting Stopping Sight Distances*, Report UMTRI-84-15, University of Michigan Transportation Research Institute, Ann Arbor, MI, 1984.)

targets and were not distracted from that task by having to drive. Roper and Howard (1938) have shown that an unexpected target is seen at about half the distance of an expected target.

How significant such detection distances are can be revealed by comparing detection distance with stopping distance for a given speed. Olson et al. (1984) have calculated stopping distances for cars and trucks when making an emergency stop from different speeds on a wet road with worn tyres, assuming a driver reaction time of 2.5 s. Two types of emergency stop were considered, one where the driver locked the wheels and hence lost control of the vehicle and one where the driver adjusted the braking so as to avoid locking the wheels (Figure 10.4). If it is assumed that the ideal situation for traffic safety is that stopping distance should equal the detection distance, it is possible to use Figure 10.4 to calculate the maximum speed for safe driving. Using the bottom of the range of detection distances found by Perel et al. (1983), such calculations suggest that the safe speed for driving on low-beam headlamps alone is about 48 km/h (30 mph).

These comparisons of detection distances and stopping distances imply that driving on low beams on unlit roads at speeds above 48 km/h (30 mph) is very much an act of faith. This might not matter so much if drivers used high beams whenever possible, that is, whenever there was no vehicle approaching and no vehicle immediately ahead. Unfortunately, field measurements have shown that this is not what happens. Sullivan et al. (2004) observed drivers' use of low and high beams on unlit rural roads. Figure 10.5 shows the percentage of drivers using high beams when there was no approaching vehicle and none immediately ahead plotted against traffic density. As might be expected, the percentage of vehicles using high beams decreases with increased traffic density, but it is not until traffic density falls below about 50 vehicles/h that high beams are used by more than about 50% of drivers. Fortunately, this pattern may soon be going to change. The technology to change between low and high beams automatically is already available (Wordenweber et al., 2007). With this technology,

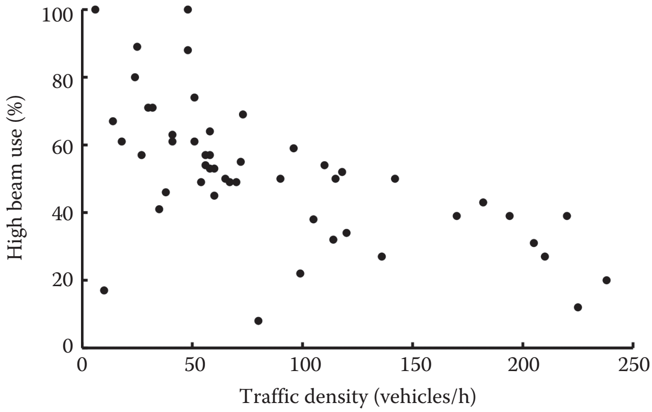


FIGURE 10.5 The percentage of drivers on unlit rural roads using headlamps on high beam when there was no approaching vehicle and none immediately ahead plotted against traffic density (vehicles/h). (After Sullivan, J.M. et al., *Lighting Res. Technol.*, 36, 59, 2004.)

the default state is high beam. Sensors detect the presence of approaching vehicles or vehicles immediately ahead and change to low beam, reverting to high beam as soon as the approaching vehicle has passed or the vehicle ahead has moved on. The widespread application of such technology would go far to minimize the risk inherent in the prolonged use of low-beam headlights on unlit roads at night.

10.2.4 Headlamps and Light Spectrum

Today, both halogen and xenon (HID) headlamps are commonly used in vehicles. HID headlamps differ from halogen headlamps in several respects, but the three that are important for visibility are the amount of light produced, the luminous intensity distribution and the spectral power distribution of the light emitted. HID headlamps typically produce two to three times more luminous flux than halogen headlamps. The recommended minimum and maximum luminous intensities used in regulations apply regardless of the light source used, a fact that raises the question of how the additional luminous flux produced by an HID light source should be distributed. The maximum luminous intensities specified in regulations are mainly restricted to the parts of the beam that cause glare to opposing drivers or drivers immediately ahead. In other parts of the beam, the regulations specify a minimum value but not a maximum. Consequently, the optics of HID headlamps are designed to direct the additional luminous flux produced by the HID light source to the parts of the beam where no maximum is specified. Figure 10.6 shows contours for the detection of a square target of 40 cm side and of reflectance 0.1 by drivers using either HID or halogen headlamps, on an ECE low-beam setting (Rosenhahn and Hamm, 2001). Clearly, the HID headlamps conforming to the same regulations allow objects to be detected at greater distances and over a wider range of angles than the halogen headlamps. It is also worth noting that the locations where there is close agreement in detection distances for the two headlamp types are the locations where the maximum luminous intensities are specified in regulations.

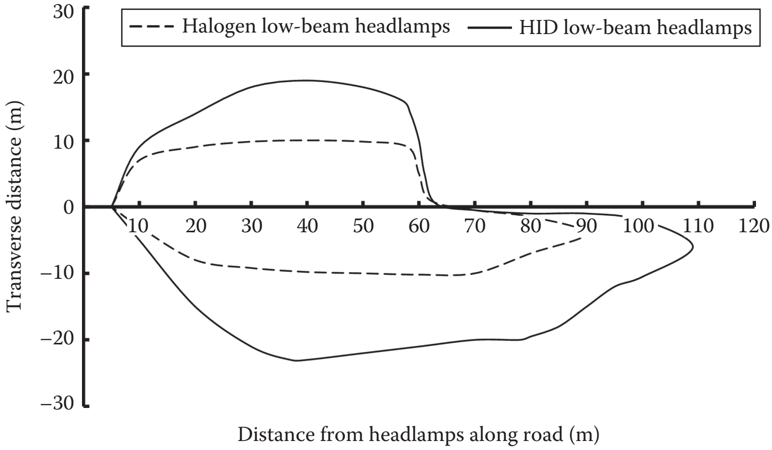


FIGURE 10.6 Contours for the distances (m) at which a square target of 40 cm side, with a reflectance of 0.1, is detected by drivers using either HID headlamps or halogen headlamps, both on low beam. (After Rosenhahn, E.O. and Hamm, M., *Measurements and Ratings of HID Headlamp Impact on Traffic Safety Aspects*, SAE Report, SP1595, Society of Automotive Engineers, Warrendale, PA, 2001.)

Van Derlofske et al. (2001) report another way of quantifying the benefits of HID over halogen headlamps. They measured reaction times to the onset of a change in reflectance of targets at various angles off-axis when illuminated by an HID headlamp set and two halogen headlamp sets, all conforming to ECE regulations and used on low beam. Figure 10.7 shows the geometry of the experiment as set out on an unused and unlit asphalt runway. The targets were placed on an arc of radius 60 m from the headlamps. Each target consisted of a 178 mm square grid of 12.7 mm diameter flip dots, each dot being a disc painted black on one side and white on the other. By applying current to the target, the dots are flipped over within 20 ms, thereby changing the target from a black square to a grey square, grey because each dot is surrounded by a black frame and at 60 m, the dots and the frame merge and together appear grey with an average reflectance of 0.4. The luminance of the target varies with position because the illuminance on the target also varies with position. Figure 10.8 shows the illuminances on each target produced by the three headlamp sets.

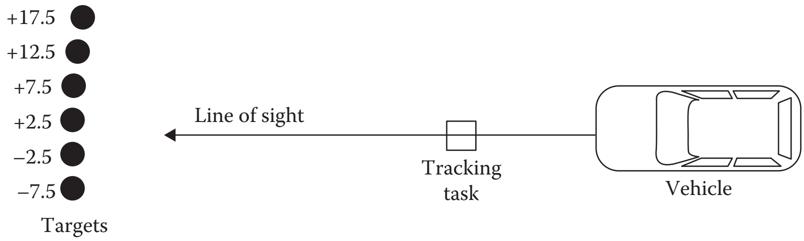


FIGURE 10.7 Geometry of the experiment conducted by van Derlofske et al. (2001). The subject sat in the test vehicle and did the continuous tracking task. The headlamps were mounted on the lamp rack at the front of the vehicle. The flip dot targets were positioned on an arc 60 m away from the headlamps spaced at 5° intervals.

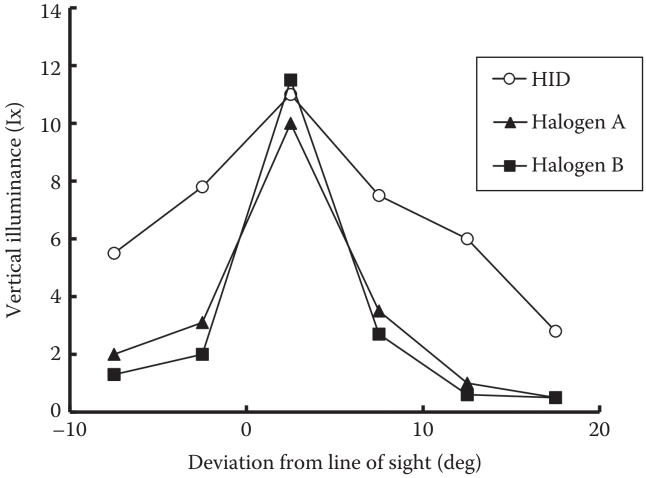


FIGURE 10.8 Illuminance (lx) on the flip dot targets produced by one HID headlamp set and two different halogen headlamp sets, all conforming to ECE regulations and used on low beam, plotted against deviation from the line of sight in degrees. (After van Derlofske, J. et al., *Evaluation of High-Intensity Discharge Automotive Forward Lighting*, SAE Technical Paper 2001-01-0298, Society of Automotive Engineers, Warrendale, PA, 2001.)

The participants performed a continuous tracking task, designed to maintain fixation directly ahead and released a press switch as soon as they detected the change in reflectance of any of the targets. The reaction time to the onset of the target, that is, the change from black to grey, was measured. Any response longer than 1 s was taken as a miss, although each such miss was included in the data from which mean reaction time was calculated at an assumed reaction time of 1000 ms. Figures 10.9 and 10.10 show the mean reaction times to the onset of the target and the percentage of missed signals, respectively, plotted against deviation from the line of sight, for the three headlamp sets. An examination of Figures 10.9 and 10.10 shows there is little difference between the three headlamp sets for less than +7.5° deviation, but beyond this, the HID headlamps give statistically significantly lower values of mean reaction time and percentage of missed signals than either of the halogen headlamp sets.

This difference between headlamp sets is what might be expected from the illuminances they produce on the targets (Figure 10.8). However, the HID and halogen headlamp sets differ in spectral power distribution as well as illuminance, and there is evidence that at low light levels, light sources that provide greater stimulation to the rod photoreceptors allow faster reaction times off-axis than light sources that do not (see Section 10.4.3). This implies that HID headlamps should allow faster reaction times for off-axis detection than halogen headlamps, even when both provide the same photopic illuminance. Van Derlofske and Bullough (2003) have examined this possibility with the same equipment and protocol as that described earlier but using a filtered HID headlamp set. The headlamp set conformed to American regulations for low beam. The filtering changed the spectral power distribution of the light but not the luminous intensity distribution or the illuminances on the targets.

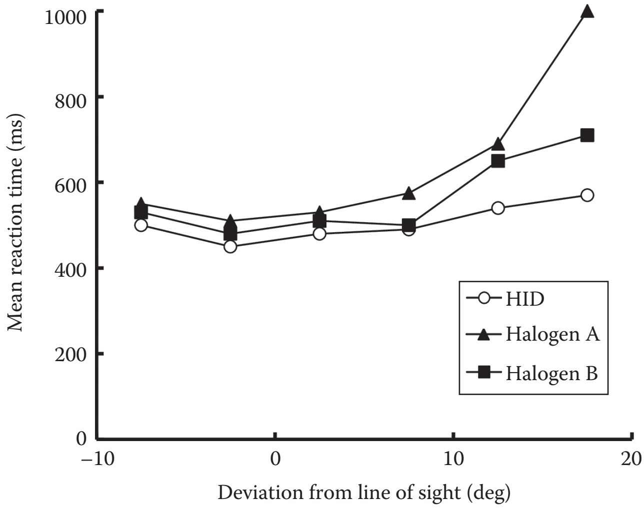


FIGURE 10.9 Mean reaction times (ms) to the onset of the targets for one HID headlamp set and two different halogen headlamp sets, all conforming to ECE regulations and used on low beam, plotted against deviation from the line of sight in degrees. (After van Derlofske, J. et al., *Evaluation of High-Intensity Discharge Automotive Forward Lighting*, SAE Technical Paper 2001-01-0298, Society of Automotive Engineers, Warrendale, PA, 2001.)

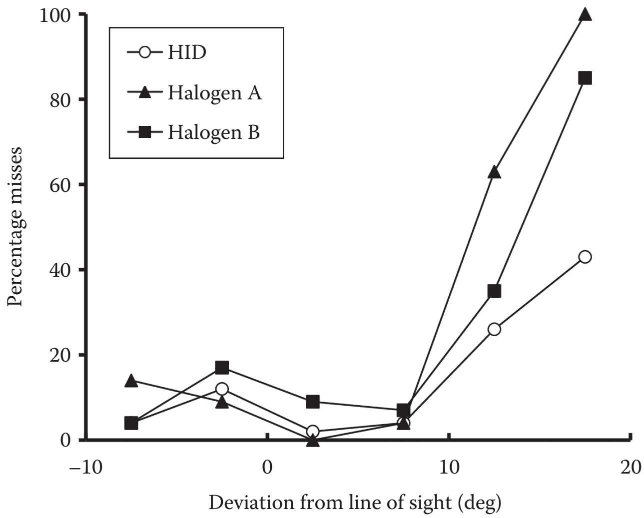


FIGURE 10.10 Percentage of missed signals for one HID headlamp set and two different halogen headlamp sets, all conforming to ECE regulations and used on low beam, plotted against deviation from the line of sight in degrees. (After van Derlofske, J. et al., *Evaluation of High-Intensity Discharge Automotive Forward Lighting*, SAE Technical Paper 2001-01-0298, Society of Automotive Engineers, Warrendale, PA, 2001.)

For each position, two target average reflectances, 0.4 and 0.2, were created by having the target viewed with and without a neutral density filter in front of it. Four different spectral power distributions were examined, the relative efficiency of each at stimulating the rod and cone photoreceptors being quantified by the S/P ratio (see Section 1.6.4.5). Figures 10.11 and 10.12 show the mean reaction times and

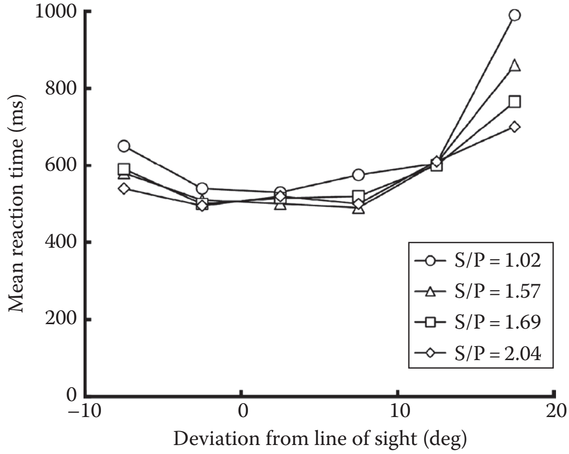


FIGURE 10.11 Mean reaction times (ms) to the onset of the low-reflectance (0.2) target for four different light spectra specified by the S/P ratio, plotted against deviation from the line of sight in degrees. (After van Derlofske, J. and Bullough, J.D., *Spectral Effects of High-Intensity Discharge Automotive Forward Lighting on Visual Performance*, SAE Technical Paper 2003-01-0559, Society of Automotive Engineers, Warrendale, PA, 2003.)

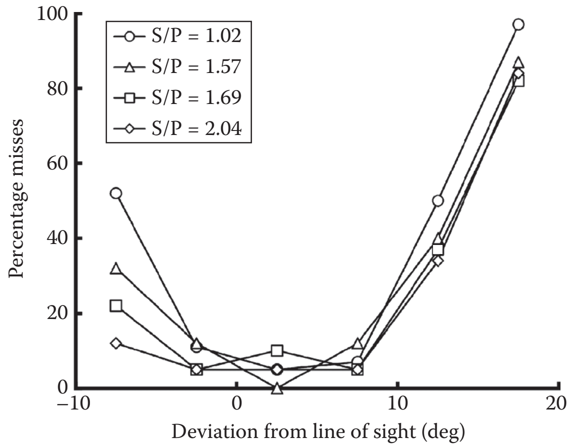


FIGURE 10.12 Percentage of missed signals for the low-reflectance (0.2) target for four different light spectra specified by the S/P ratio, plotted against deviation from the line of sight in degrees. (After van Derlofske, J. and Bullough, J.D., *Spectral Effects of High-Intensity Discharge Automotive Forward Lighting on Visual Performance*, SAE Technical Paper 2003-01-0559, Society of Automotive Engineers, Warrendale, PA, 2003.)

the percentage of missed signals, respectively, for the 0.2 average reflectance target, plotted against deviation from the line of sight, for each spectral power distribution.

A common pattern is evident in Figures 10.11 and 10.12. Mean reaction times and the percentages of missed signals increase with increased deviation from the line of sight, for all spectral power distributions. These increases are certainly due to the decrease in illuminance on the target as deviation from the line of sight increases (Figure 10.8). However, at the extreme deviations, where the illuminances on the targets are least, an effect of spectral power distribution is evident. Specifically, the mean reaction time and the percentage of missed signals both decrease as the S/P ratio of the light source increases. This is what would be expected from what is known about how the spectral sensitivity of off-axis vision changes in the mesopic state (see Section 2.3.2) and indicates that HID headlamps have an additional advantage for off-axis visibility over and above the greater illuminances produced. Although real, this advantage is small relative to the impact of the greater illuminances. This became apparent when the data for the 0.4 average reflectance targets were examined. For these data, the increases in mean reaction times and percentages of missed signals with increasing deviation from the line of sight were present and of similar magnitude to those obtained for the 0.2 average reflectance targets, but there was no statistically significant effect of S/P ratio.

10.2.5 Glare from Headlamps

There are several different forms of glare, but the main form of interest when considering headlamps is disability glare (see Section 5.4.2.1). The CIE has developed a disability glare formula suitable for use with headlamps. The CIE formula applies at all angles from the line of sight in the range 0.1°–30° and to either young or old people (CIE, 2002b). This equation takes the form

$$L_v = \Sigma\left(\frac{10E_n}{\Theta_n^3} + \left(1 + \left(\frac{A}{62.5}\right)^4\right)\left(\frac{5E}{\Theta_n^2}\right)\right)$$

where

L_v is the equivalent veiling luminance (cd/m^2)
E_n is the illuminance (lx) at the observer's eyes from the nth glare source
Θ is the angle of the nth glare source from the line of sight (degrees)
A is the age of the observer (years)

The effect of the equivalent veiling luminance on the luminance contrast of an object can be estimated by adding it to the luminance of both the object and the immediate background (see Section 2.4.1.1).

The only photometric quantity relevant to equivalent veiling luminance is the illuminance from the glare source received at the eye. There is little evidence for other aspects of exposure, such as the illuminated area of the headlamp and the light spectra influencing disability glare. Van Derlofske et al. (2004) examined the impact of different illuminances at the eye on the ability to detect off-axis targets using the same equipment and protocol as that described earlier (see Figure 10.7) but using another HID headlamp set positioned 50 m ahead and 5° to the left of the subject's line of sight. The HID headlight set was tilted slightly to produce three different illuminances at the subject's eyes: 0.2, 1.0 and 5.0 lx. Each flip dot target was presented with and without a neutral density filter placed in front, the result being that the average reflectance of the target was, when presented, either 0.4 or 0.2. Again, the subjects performed a continuous tracking task to control fixation and released a button when they detected a change in one of the targets. Any change that was not detected within 1 s was counted as a missed target and included in the data used to calculate mean reaction time as a reaction time of 1000 ms. Figures 10.13 and 10.14 show the mean reaction times and percentage of missed signals plotted against the target position relative to the line of sight, for the three illuminances at the eye and the two target average reflectances. Also shown are the predicted percentages of missed targets when no glare source is present, based on the model of Bullough (2002a). The first point to note about Figures 10.13 and 10.14 is that the mean reaction times for targets of both reflectances positioned at –2.5° and 17.5° are concentrated at 1000 ms. This is because for these two positions, virtually all the targets were missed. The targets at –2.5° were closest to the glare source, and those at 17.5° were furthest from the glare source. The reason for the missed targets at –2.5° is the reduction in luminance contrast caused by the disability glare produced by the glare source, an observation supported by the low level of misses predicted for

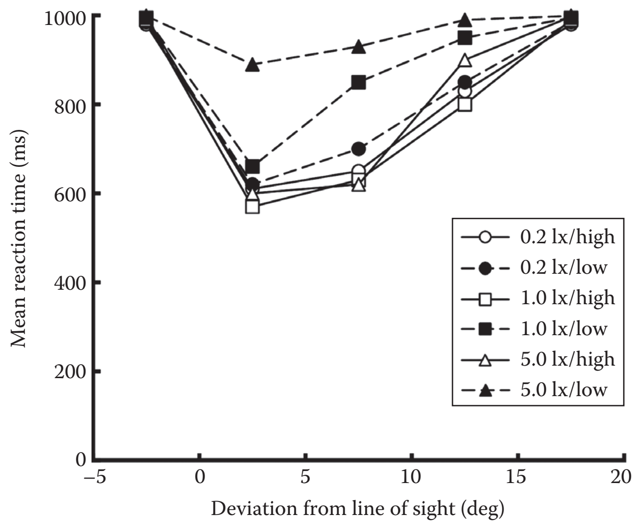


FIGURE 10.13 Mean reaction times (ms) to the onset of the high- (0.4) and low-reflectance (0.2) targets for three different levels of disability glare specified by the illuminance (lx) received at the eye, plotted against deviation from the line of sight in degrees. (After van Derlofske, J. et al., *Headlamp Parameters and Glare*, SAE Technical Paper 2004-01-1280, Society of Automotive Engineers, Warrendale, PA, 2004.)

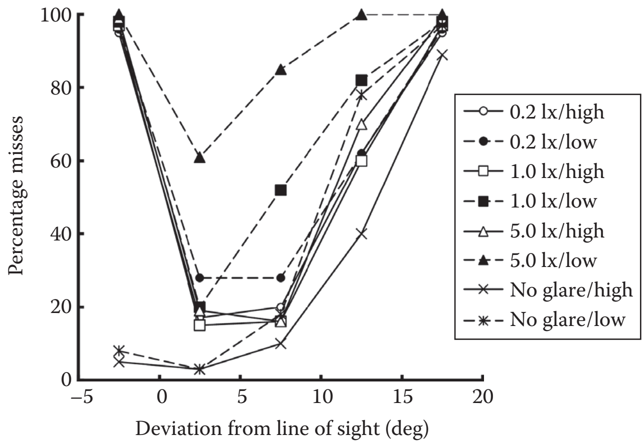


FIGURE 10.14 Percentage of missed high- (0.4) and low-reflectance (0.2) targets for three different levels of disability glare specified by the illuminance (lx) received at the eye, plotted against deviation from the line of sight in degrees. Also shown are the percentages of missed targets in the absence of glare predicted by the model of Bullough (2002a). (After van Derlofske, J. et al., *Headlamp Parameters and Glare*, SAE Technical Paper 2004-01-1280, Society of Automotive Engineers, Warrendale, PA, 2004.)

the –2.5° position in the absence of opposing headlamps. Even an illuminance at the eyes as low as 0.2 lx ensures the target at –2.5° will be missed. This is bad news for any pedestrian caught behind two opposing vehicles when attempting to cross the road. The reason for the missed targets at 17.5° is not disability glare but rather the failure of the subject's headlamps to illuminate the target. For the other positions, 2.5°, 7.5° and 12.5° from the line of sight, it is clear that reaction times increase and percentage of misses increases with increasing deviation from the line of sight and that these increases are much greater for the low average reflectance than for the high average reflectance targets. The difference between the low and high average reflectance targets is to be expected because the effect of a given equivalent veiling luminance on visibility will depend on the luminance contrast of the target. The low average reflectance target will have a lower luminance contrast with its immediate background in the absence of glare, so the addition of the veiling luminance will take the low average reflectance target closer to threshold than it will on the high average reflectance target. The effect of the illuminance at the eyes is only evident at 2.5°, 7.5°, and 12.5° from the line of sight for the low-reflectance ($p = 0.2$) target. For this target, a glare illuminance of 0.2 lx has hardly any effect on mean reaction time and the percentage of missed targets, but glare illuminances of 1.0 and 5.0 lx both cause increases in mean reaction times and percentage of targets missed, the increases for 5.0 lx being much greater than for 1.0 lx.

There can be no doubt that a driver facing oncoming headlamps will experience a reduction in his ability to detect targets that are close to threshold in the absence of glare (see Figure 10.14). However, the measurements on which this conclusion is based were taken in a static situation, but glare is most usually experienced in a dynamic situation as two vehicles approach and pass each other. Mortimer and Becker (1973),

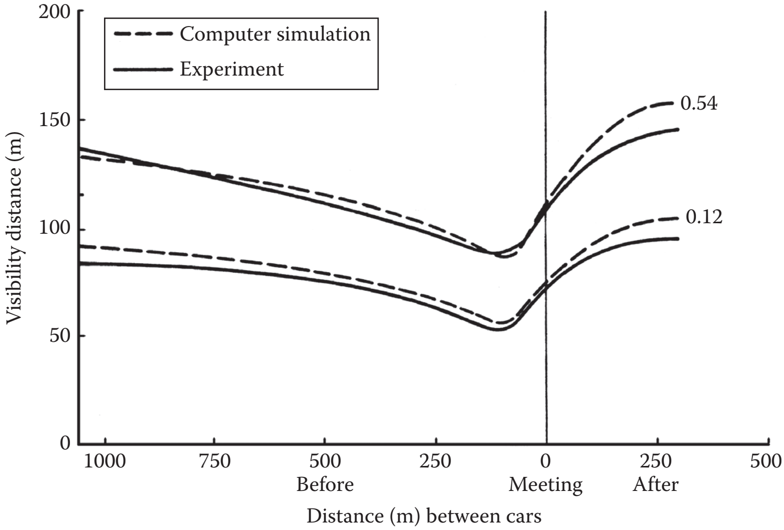


FIGURE 10.15 Visibility distance (m) for targets of reflectance 0.54 and 0.12, plotted against the distance (m) between two vehicles approaching each other, with headlamps of equal luminous intensity. (After Mortimer, R.G. and Becker, J.M., *Development of a Computer Simulation to Predict the Visibility Distances Provided by Headlamp Beams*, Report UM-HSRI-IAF-73-15, University of Michigan, Ann Arbor, MI, 1973.)

using both computer simulation and field measurements, have shown that the distances at which targets of reflectances 0.54 and 0.12 become visible diminish as opposing cars close and then start to increase rapidly (Figure 10.15). The separation at which the visibility distance is a minimum depends on the relative luminous intensity distribution of the headlamps, the relative positions of the two vehicles, the obstacles to be seen and the physical characteristics of the obstacle.

Helmers and Rumar (1975) measured visibility distances for flat, dark-grey 1.0 m by 0.4 m rectangles with a reflectance of 0.045. Observers were driven towards a parked car with its headlamps on and asked to indicate when they saw the obstacles. It was found that for the small dark-grey obstacle, a headlamp system with the maximum high-beam luminous intensity gives a visibility distance of about 220 m when no opposing vehicle is present. This is the same as the stopping distance for a vehicle moving at 110 km/h (68 mph) on wet roads (AASHTO, 2001). However, when two opposing vehicles have equal luminous intensity headlamps, the visibility distance is reduced to about 60–80 m, which is much less than the stopping distance, and when the opposing vehicle had a luminous intensity about three times more than the observer's vehicle, the visibility distance is reduced to about 40–60 m. Again, it is clear that driving at high speeds against opposing traffic at night approaches an act of faith.

The difficulty in seeing experienced by drivers when exposed to approaching headlamps is replaced by a feeling of relief almost immediately after the other vehicle passes as the light scattered in the eye vanishes. Unfortunately, that does not mean

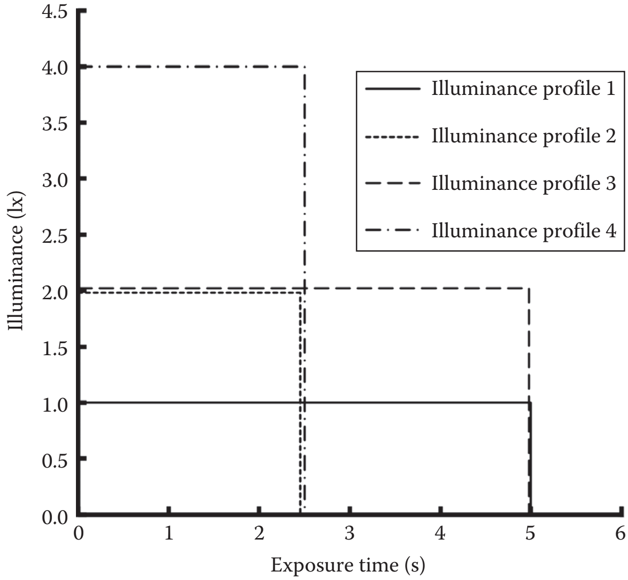


FIGURE 10.16 The four glare stimuli used by van Derlofske et al. (2005) showing the illuminance at the eye (lx) and the duration of exposure (s). The effect of these stimuli is to produce three different maximum illuminances and two different light doses.

that vision is immediately restored to the state that existed before exposure to glare. The additional light that has reached the retina of the driver from the approaching headlamps will have had an effect on the state of adaptation of the photoreceptors, so immediately after the other vehicle passes, the driver's vision will be misadapted. The process of adjusting adaptation is called recovery from glare. Van Derlofske et al. (2005) examined what factors determined the time taken to recover from glare. The observer was exposed to four different glare stimuli (Figure 10.16) differing in maximum illuminance and light dose, this latter being the product of illuminance and time duration of exposure. Specifically, illuminance profiles 1 and 2 had different maximum illuminances but the same light dose. Illuminance profiles 3 and 4 also had different maximum illuminances but the same light dose, although the light dose was twice that of illuminance profiles 1 and 2. Immediately after exposure, the observer was presented with a square target, the contrast of which was a fixed ratio of the individual's threshold contrast, that is, at a fixed visibility level. The observer's task was to indicate when the target could first be detected. Figure 10.17 shows the mean detection times for different target contrast ratios and for the different glare exposure profiles. From Figure 10.17, it is evident that detection times are shorter for the higher-contrast target ratios and that the detection time is determined by the light dose and not the maximum illuminance.

Although difficulty in seeing is the most important effect of facing approaching headlamps, there is also a feeling of discomfort. Schmidt-Clausen and Bindels (1974) produced an equation relating the illuminance at the eye to the level of discomfort produced by headlamps, expressed on the de Boer scale. The equation is

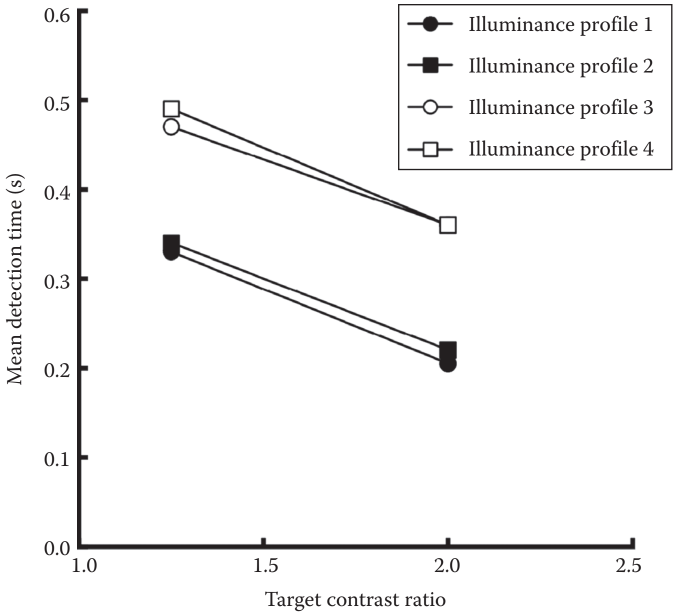


FIGURE 10.17 Mean detection time (s) for targets after exposure to the four glare stimuli shown in Figure 10.16 plotted against target contrast ratio. Target contrast ratio is the ratio of the actual contrast to the threshold contrast without glare. (After van Derlofske, J. et al., *Headlight Glare Exposure and Recovery*, SAE Paper 05B-269, Society of Automotive Engineers, Warrendale, PA, 2005.)

$$W = 5.0 - 2\log\left[\frac{E}{0.003\left(1+\sqrt{(L/0.04)}\right)\phi^{0.46}}\right]$$

where

W is the discomfort glare rating on the de Boer scale
E is the illuminance at the observer's eyes (lx)
L is the adaptation luminance (cd/m^2)
ϕ is the angle between the line of sight and the glare source (min arc)

The de Boer scale is a nine-point glare scale with five anchor points labelled 1 = unbearable, 3 = disturbing, 5 = just admissible, 7 = acceptable and 9 = unnoticeable. Note that on this scale, lower values are more uncomfortable. Conditions producing ratings of 4 or less are usually considered uncomfortable.

Figure 10.18 shows the mean ratings of discomfort glare plotted against the illuminance at the eye from the HID headlamps in the experiment of Van Derlofske et al. (2004) described earlier. Also shown are the ratings predicted by the Schmidt-Clausen and Bindels discomfort glare equation for the same experimental situation. The predictions of the discomfort glare equation show a broad agreement with the findings for the low-reflectance target of Van Derlofske et al. (2004). More interesting

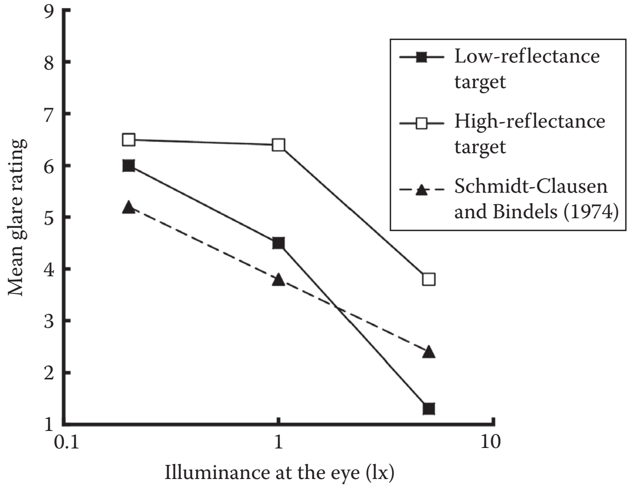


FIGURE 10.18 Mean discomfort glare (de Boer) ratings collected when the subject was attempting to detect the onset of low- (0.2) and high-reflectance (0.4) off-axis targets, plotted against the illuminance (lx) received at the eye. Also shown are the predicted glare ratings derived from the discomfort glare equation of Schmidt-Clausen and Bindels (1974). (After van Derlofske, J. et al., *Headlamp Parameters and Glare*, SAE Technical Paper 2004-01-1280, Society of Automotive Engineers, Warrendale, PA, 2004.)

is the finding that there is a clear difference between the low- and high-reflectance targets. This implies that the perception of discomfort glare depends not only on the stimulus to the visual system produced by the glare source but also on what the observer is trying to do. This should not be too surprising given that it is well known that the same photometric stimuli can be considered as comfortable or uncomfortable depending on the task being performed (Sivak et al., 1991).

The discomfort glare equation produced by Schmidt-Clausen and Bindels (1974) involves three components: the illuminance at the eye, the adaptation luminance and the angle between the glare source and the line of sight. However, there is evidence that light spectrum (Flannagan et al., 1989; van Derlofske et al., 2004), glare source size (van Derlofske et al., 2004), background luminance (Bullough, 2011) and maximum glare source luminance (Bullough and Sweater Hickcox, 2012) all have effects. The direction of these effects is such that for the same illuminance at the eye, light spectra with more energy at the short-wavelength end of the visible spectrum produced by smaller-size headlamps will tend to cause slightly more discomfort, but that discomfort will be diminished as the background luminance increases. As for the effect of maximum glare source luminance, this depends on glare source size. For glare sources subtending angles less than 0.3°, the maximum glare source luminance has little effect on discomfort, but for larger sources, for the same illuminance at the eye, higher maximum source luminances cause more discomfort.

Bullough et al. (2008) have proposed an alternative model of discomfort glare from outdoor lighting, based on the illuminances received at the eye from various parts of the visual environment (see Section 11.4). The range of illuminance received at the eye during normal driving is from 0 to 10 lx (Alferdinck and Varkevisser, 1991).

Illuminances of 3 lx and more are likely to be considered very uncomfortable (Bullough et al., 2002). Illuminances of the order of 1–3 lx are sufficient to cause drivers to request dimming from the approaching vehicle (Rumar, 2000). Given that the approaching driver does not respond to a request for dimming, how does the requesting driver respond? Theeuwes and Alferdinck (1996) had people drive over urban, residential and rural roads at night, with a glare source simulating the headlamps of an approaching vehicle mounted on the bonnet of the car. They found that people drove more slowly when the glare source was on, particularly on dark winding roads where lane keeping was a problem. Older drivers showed the largest speed reduction.

From the discussion earlier, it is possible to understand the widespread complaint that HID headlamps produce worse glare conditions than halogen headlamps. This is mainly because the light distributions of HID headlamps typically have higher maximum luminous intensities than halogen headlamps and put more light to the sides of the vehicle in areas where the maximum luminous intensity is not controlled by the current regulations. These differences in the amount and distribution of light emitted between HID and halogen headlamps imply that HID headlamps will produce higher illuminances, for longer, at the eyes of a driver meeting a car equipped with HID headlamps. Consequently, the reduction in visibility, the level of discomfort and the time for recovery from glare should usually be longer when meeting a vehicle fitted with HID headlamps.

These differences between HID and halogen headlamps are all to do with differences in the illuminances produced at the eye, but there is another difference between these light sources. The spectral power distribution of the HID headlamp has much more energy at the short-wavelength end of the visible spectrum than the halogen headlamp. This alone will tend to lead to greater discomfort from the HID headlamp for the same illuminance at the eye (Bullough et al., 2003). Figure 10.19 shows the mean ratings of discomfort on the de Boer scale for halogen and HID headlamps positioned at 5° and 10° from the line of sight and plotted against the illuminance at the eye (Bullough et al., 2002). As would be expected, both the illuminance at the eye and the deviation from the line of sight show statistically significant effects on the magnitude of discomfort glare but so does light spectrum.

To evaluate the effect of any specific headlamp light spectrum on discomfort glare, a spectral sensitivity curve has been proposed (Bullough, 2009):

$$V_{dg}(\lambda) = V_{10}(\lambda) + k \times \mathrm{SWC}(\lambda)$$

where

$V_{dg}(\lambda)$ is the discomfort glare spectral sensitivity
$V_{10}(\lambda)$ is the photopic spectral sensitivity for a 10° field
k is a constant
SWC (λ) is the short-wavelength cone spectral sensitivity

The constant k has been found to vary with eccentricity from the line of sight, indicating greater influence of the short-wavelength cones at greater eccentricities. For 5° eccentricity, $k = 0.19$, but for 10° eccentricity, $k = 0.75$. This model implies that when LEDs become suitable for use in headlamps, it will be necessary to select their light spectrum carefully if discomfort glare is not to be increased.

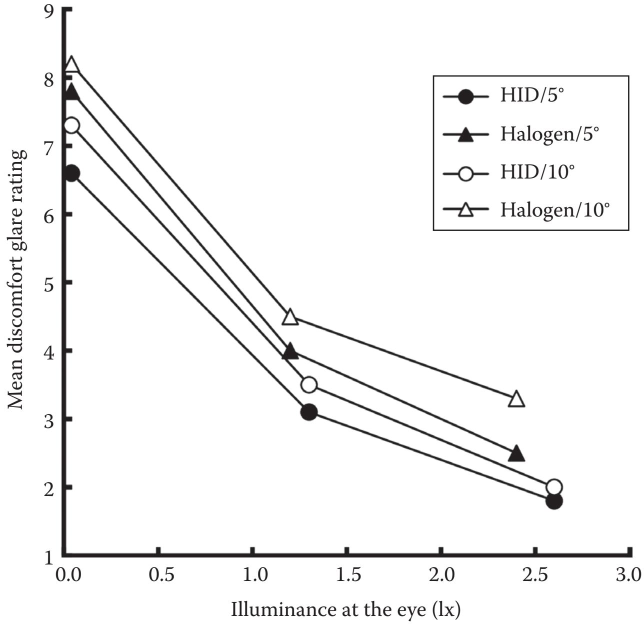


FIGURE 10.19 Mean discomfort glare (de Boer) ratings for exposure to halogen and HID headlamps at 5° and 10° from the line of sight plotted against the illuminances (lx) at the eye. (After Bullough, J.D. et al., *Discomfort and Disability Glare from Halogen and HID Headlamp Systems*, SAE Paper 2002-01-1-0010, Society of Automotive Engineers, Warrendale, PA, 2002.)

10.2.6 Fog Lamps

One supplementary form of forward lighting found on some vehicles is the fog lamp. Fog lamps are mounted low on the vehicle, below the other forward lighting, and have a luminous intensity distribution that is both wide and flat, the effect being to put more light on the road immediately in front and to the sides of the vehicle and very little above the horizontal plane through the fog lamps. The low mounting position is advantageous because fog is usually thinner near the road surface. The minimizing of the light distribution above the horizontal is desirable because light directed upwards would intersect the driver's line of sight close to the vehicle and hence increase the veiling luminance arising from the light scattered by the water droplets forming the fog.

The visual effect of fog lamps is to provide greater visibility of road edges and nearby lane markings, thereby making lane keeping easier. Fog lamps do little to enhance the visibility of vehicles and objects further along the road. Figure 10.20 shows the calculated luminance contrasts of road markings for fog lamps alone, low-beam headlamps alone and both fog lamps and low-beam headlamps 10, 20 and 40 m ahead of the vehicle, in a clear atmosphere and in light, medium and heavy fog (Folks and Kreysar, 2000). Figure 10.20 clearly demonstrates the impact of fog density on visibility by showing a marked reduction in luminance contrast with

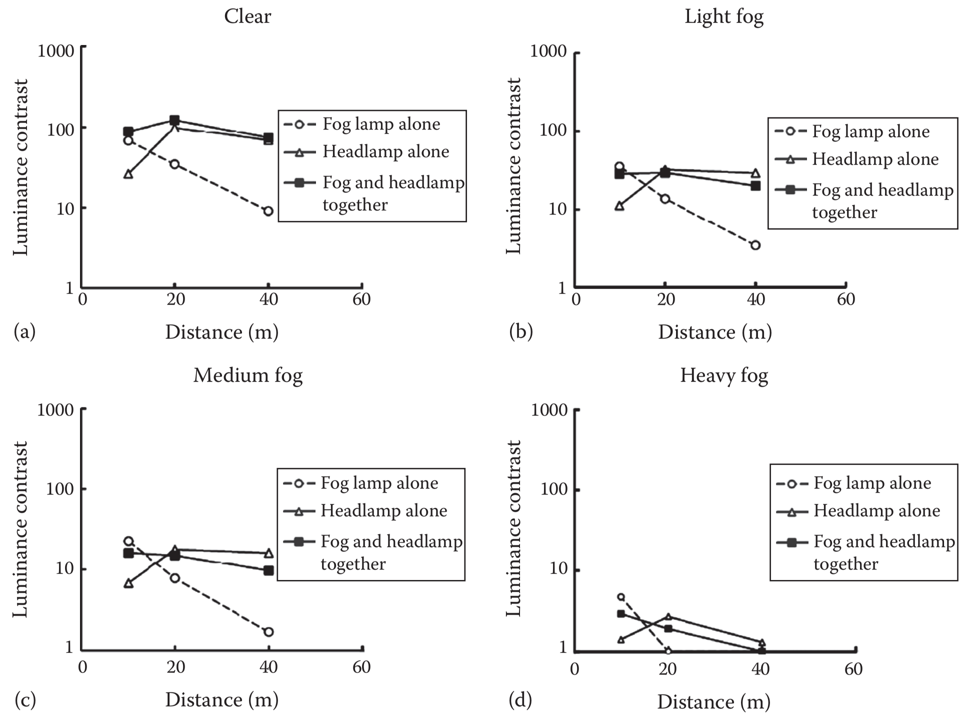


FIGURE 10.20 Calculated luminance contrasts for road markings of reflectance 0.5 in (a) clear atmosphere, (b) light fog, (c) medium fog and (d) heavy fog, for fog lamps alone, low-beam headlamps alone and both fog lamps and low-beam headlamps together, the markings being placed at distances of 10, 20 and 40 m in front of the vehicle. The calculations are made for fog lamps mounted at 0.4 m above the road, eye height at 1.42 m above the road and a background luminance of 0.017 cd/m^2 in a clear atmosphere. The extinction coefficients for the four atmospheres are clear = 0.00015 m^{-1}, light fog = 0.003 m^{-1}, medium fog = 0.006 m^{-1} and heavy fog = 0.03 m^{-1}. (After Folks, W.R. and Kreysar, D., *Front Fog Lamp Performance*, *Human Factors in 2000, Driving, Lighting, Seating Comfort and Harmony in Vehicle Systems*, Report SP-1539, Society of Automotive Engineers, Warrendale, PA, 2000.)

increasing fog density at all three distances. As for the best form of lighting to use, in a clear atmosphere, adding fog lamps to low-beam headlamps increases the luminance contrast at all three distances, although the increase diminishes with distance. In light, medium and heavy fogs, fog lamps alone produce the highest luminance contrast at 10 m, but low-beam headlamps alone ensure higher luminance contrasts at 40 m. Clearly, vehicle forward lighting alone has its limitations for ensuring traffic safety in fog (Flannagan, 2001).

10.2.7 Innovations

So far, attention has been concentrated on the headlamps that are fitted to the vast majority of vehicles on the roads, headlamps that use either halogen or HID light sources that have two possible states, high and low beam, each producing luminous intensity distributions conforming to either the ECE or American regulations. However, the last few years have seen the introduction of a number of innovations in headlamps, the most dramatic of which has been the appearance of adaptive forward lighting systems. This has occurred in two stages. The first was the introduction of the bending light designed to increase visibility around a curve. Two forms of bending light are permitted. Either the headlamps are swivelled to better illuminate the curve in the road without changing the luminous intensity distribution (dynamic) or the headlamps are fixed but the luminous intensity distributions are changed by switching on additional light sources to increase the illuminance around a corner (static). Such headlamp systems are becoming available on many up-market cars. The movement or switching of the headlamp beam is automatic, determined by some combination of signals from sensors providing information on the vehicle's motion.

The next stage in the development of adaptive forward lighting involves systems to produce different luminous intensity distributions for a number of different commonly occurring driving situations. In addition to the usual low and high beams, modified luminous intensity distributions have been proposed for use in towns where speeds are low, for use on motorways and divided carriageways where speeds are high and there is a large separation between traffic streams and for use on wet roads, where the increased specular reflection leads to more glare to opposing drivers (Wordenweber et al., 2007). The transition between these beams is automatically determined by some combination of signals from sensors giving the vehicle's speed and direction, ambient light level, use of windscreen wipers and the turning of the steering wheel.

The town beam is wider than the conventional low beam and extends a shorter distance up the road, thereby emphasizing the visibility of pedestrians, road signs and road markings. In addition, the light output of the headlamp is halved. This town beam is activated when speeds are below about 50 km/h (31 mph) or if the road surface luminance is higher than 1 cd/m^2. The motorway beam is created by moving the low beam up a quarter of a degree to extend the beam further down the road. This beam is activated when the vehicle is moving over 110 km/h (68 mph). The wet road beam involves a reduction in the illumination just in front of the vehicle and increased light to the sides of the vehicle. This beam is activated when either rain is detected on the road or the windscreen wipers are switched on. Evaluations of bending lighting, motorway lighting and town lighting by drivers indicate that bending lighting is considered the most valuable, followed by motorway lighting with town lighting having the least value (Hamm, 2002). Sullivan and Flannagan (2007) have concluded that adaptive forward lighting systems have the potential to significantly reduce accidents involving pedestrians, particularly on high-speed roads.

Despite the impressive technology and engineering skill involved in developing adaptive forward lighting systems, they do not really deal with the fundamental problem of forward lighting, namely, the conflict between visibility and glare. Fortunately, there are a number of other potential solutions to the problem of maximizing visibility while minimizing glare (Mace et al., 2001). One solution is to use radiation outside the visible range to illuminate the road ahead, usually infrared (IR).

IR night vision systems come in two forms, active and passive. Active night vision systems use a headlamp emitting IR radiation in the wavelength range 800–1000 nm coupled to a camera sensitive to these wavelengths which is linked to a display available to the driver (Holz and Weidel, 1998; Wordenweber et al., 2007). Because the wavelengths used are outside the visible range, the IR headlamp can be kept on high beam even when there are opposing vehicles. This high level of IR radiation together with the fact that many materials that have a low reflectance in the visible wavelengths have a much higher reflection in the near IR means that active IR night vision systems are effective at exposing people and animals at much greater distances than would be possible using low beams alone. Passive night vision systems detect IR radiation emitted by surfaces at different temperatures, usually in the wavelength range 8–14 μm. There is no additional radiation emitted from the vehicle. Such a system is effective in detecting warm objects with a distinct temperature difference from the background, such as pedestrians and other animals, but not objects at a similar temperature as the background, such as lane markings.

Tsimhoni et al. (2005) had people perform a simulated steering task while viewing video recordings of a drive along a road where pedestrians were to be seen and the same trip as seen by active and passive night vision systems. The mean distances at which the pedestrians were detected were about three times greater for the passive night vision system than for the active night vision system. Hankey et al. (2005) report measurements of the distances at which drivers were able to detect pedestrians wearing black or white clothing, crossing or standing beside the road, with and without a passive IR system using a head-up display. The drivers were also asked to detect a pedestrian wearing white clothes standing near a stationary vehicle with its headlamps on and standing behind a crash barrier on a curve as well as a piece of tyre tread on the far side edge line. For the pedestrians crossing and standing by the road, the drivers were not aware of their location, but they were for the pedestrian near the glare source. The pedestrian standing behind the crash barrier on the curve was outside the field of view of the passive system and the tyre tread had a similar temperature to the road. Table 10.1 shows the mean detection distances for each detection task, with or without the passive system. In addition, the percentage of times the pedestrian crossing or standing beside the road was detected at less than 150 m is given as are the percentages of times the pedestrian standing by the glare vehicle or standing behind the crash barrier or the tyre tread were detected at less than 50 m. Any detection of pedestrians crossing or standing beside the road at less than 150 m was

TABLE 10.1
Mean Detection Distance (m) and Percentage of Misses for Detecting Pedestrians and Tyre Treads at Night Using Headlamps Alone or Headlamps with a Passive IR Night Vision System

	Headlamps Only		Headlamps and Passive IR Night Vision System	
Target	**Mean Distance (m)**	**Misses (%)**	**Mean Distance (m)**	**Misses (%)**
Pedestrian in black crossing road	61	31	455	0
Pedestrian in white crossing road	119	3	444	0
Pedestrian in black standing beside road	42	26	414	0
Pedestrian in white standing beside road	137	0	409	0
Pedestrian in white standing near glare vehicle	87	0	379	0
Pedestrian in white standing behind crash barrier on curve	50	12	36	29
Tyre tread on far side edge line	49	6	44	23

Source: Hankey, J.M. et al., *Quantifying the Pedestrian Detection Benefits of the General Motors Night Vision System*, SAE Technical Paper 2005-01-0443, Society of Automotive Engineers, Warrendale, PA, 2005.

counted as a miss and given a detection distance of 0 m. Similarly, any detection of pedestrians beside the glare vehicle or behind the crash barrier or the tyre tread that occurred at less than 50 m was counted as a miss and given a detection distance of 0 m. An examination of Table 10.1 reveals large, statistically significant increases in mean detection distances as well as zero misses for pedestrians crossing and standing beside the road and standing beside the glare vehicle, when the passive system is operating. When it is not operating, the increased mean detection distances for pedestrians wearing high-reflectance clothing are clear. Another interesting point is that mean detection distance for the pedestrian standing behind the crash barrier on a curve is statistically significantly shorter, and there are more misses when the passive system is operating than when headlamps alone are used. This pedestrian is outside the field of view of the passive system, suggesting that when the passive system is used, attention is focused on the area it covers. Nonetheless, the greatly increased detection distances for pedestrians on or close to the road, who are much more at risk than a pedestrian standing behind a crash barrier, are clear.

By now, it should be apparent that this is an exciting time to be involved in the design of vehicle forward lighting. After decades of little change, there are now many possibilities for enhancing the ability of the driver to see the road ahead without blinding those approaching. Some of these possibilities are evolutionary in that they involve introducing more beam types and more automation to the existing high-beam/low-beam options. Others are revolutionary in that they offer additional information based on parts of the electromagnetic spectrum outside the visible. Presently, these possibilities are used to supplement human vision but they may ultimately replace it. It will be interesting to see which of these possibilities thrive and which decline.

10.3 VEHICLE SIGNAL LIGHTING

Signal lighting is designed to indicate the presence or give information about the movement of a vehicle. Some signal lamps, such as front and rear position lamps and side marker lamps, are used only at night or in conditions of poor daytime visibility, while others, such as turn lamps and stop lamps, have to be visible at all times, both day and night.

10.3.1 Technology

For many years, the technology of vehicle signal lighting hardly changed, consisting of little more than an incandescent light source covered by a clear or coloured lens. However, over the last decade, this situation has been transformed. Today, signal lighting uses a variety of light sources and methods of optical control and is an integral part of the styling of the vehicle (Wordenweber et al., 2007). The incandescent lamp has the advantage of being simple and inexpensive but has the disadvantage of requiring regular replacement throughout the life of the vehicle. This problem is overcome by the LED light source. LEDs have much longer lives than incandescents, so much so that they should not need to be replaced during the life of the vehicle. LEDs have other advantages. To create a coloured signal, the incandescent has to be filtered, while the LED, if judiciously chosen, emits light of the desired colour, without filtering. This means that LED signal lamps have smaller power demands than incandescent signal lamps fulfilling the same function. LEDs, being solid-state devices, are also less sensitive to vibration than light sources that rely on a heated filament and, because they are smaller, offer the designer a wider range of possibilities. LEDs are rapidly becoming the light source of choice for vehicle signal lighting.

The regulations applicable to signal lighting specify different luminous intensity distributions for each signal function. To meet these regulations, signal lamps require some form of optical control. There are three such systems used in signal lamps based on reflection, refraction and total internal reflection (Wordenweber et al., 2007). For the reflector system, the light distribution is determined by the position of the light source relative to the reflector, the shape of the reflector, and any optical patterning of the front cover glass. For the refractor system, a Fresnel lens cover glass is used. As for total internal reflection, this is the physical principle used in light guides. A light guide consists of a transparent material with a refractive index higher than the surroundings, which for motor vehicles is air. LEDs are the preferred light source for light guides; their low temperature and small size make it easy to couple LEDs closely to the light guide. The light distribution is largely determined by the prismatic element used to extract light from the light guide. One other aspect of signal lighting design that has changed considerably over the years is the packaging of the signal lamps. Today, rather than having individual signal lamps, it is usual to package them into a common structure called a cluster. Despite this common structure, each individual signal lamp has to meet its own set of regulations.

10.3.2 Regulation

The visibility of a signal lamp depends on its luminance, size, shape and colour, the background against which it is seen and the state of adaptation of the driver. Much effort has been put into measuring the minimum values of some of these variables necessary to make the signal lamp visible under different conditions (Dunbar, 1938; de Boer, 1951; Moore, 1952; Hills, 1975; Sivak et al., 1998). Figure 10.21 shows the relationship between luminance and size for red rear position lamps, disc obstacles and pedestrian dummies to be just visible, that is, at threshold, under no road lighting and no glare conditions (Hills, 1976). It can be seen that log luminance plotted against log visual area gives a nearly straight line; the smaller is the signal area, the greater its luminance has to be before it is just visible.

Using data similar to that shown in Figure 10.21, Hills (1976) produced a predictive model of the relationship between luminance increment and area for small objects to be just visible for a wide range of background luminances (Figure 10.22). A small object in this model is one for which spatial summation occurs in the visual system. For foveal vision, spatial summation is complete within a circle of diameter subtending about 6 min arc. For targets that occur 5° off-axis, spatial summation occurs over a circle of diameter about 0.5° (Boff and Lincoln, 1988). Given the usual size of signal lamps and the distance from which they need to be seen, spatial summation should apply. The ordinate in Figure 10.22 is the logarithm of the increment of the object luminance necessary for it to be just visible against the background luminance. Different values of background luminance enable the effects of different lighting conditions to be estimated, from starlight, through road lighting, to daylight. Hills (1976) also shows that by using such curves, he can plausibly predict the field results

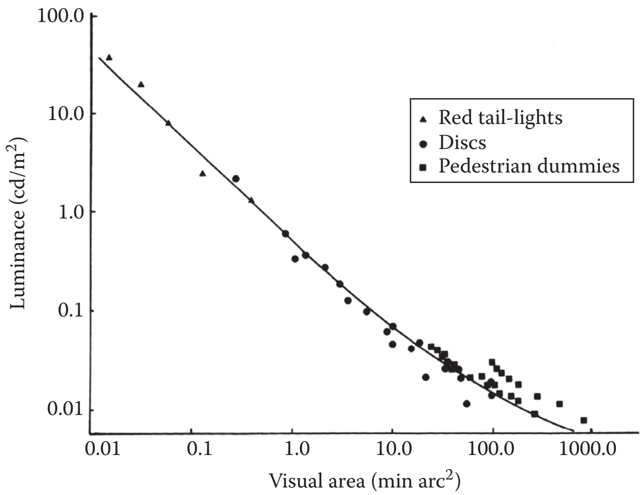


FIGURE 10.21 The relationship between luminance (cd/m^2) and visual area (min arc^2) for rear position lamps (red tail lights), discs and pedestrian dummies to be *just visible* under no road lighting/no glare conditions. (After Hills, B.L., *Lighting Res. Technol.*, 8, 11, 1976.)

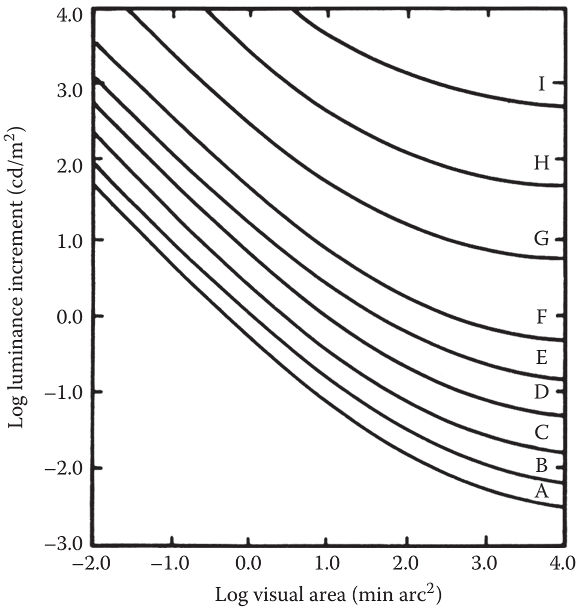


FIGURE 10.22 Relationships between luminance increment (cd/m^2) and visual area (min arc^2) at different background luminances, for small targets to be just visible. Each curve is for one background luminance as follows: A = 0.01 cd/m^2, B = 0.1 cd/m^2, C = 0.32 cd/m^2, D = 1.0 cd/m^2, E = 3.2 cd/m^2, F = 10 cd/m^2, G = 100 cd/m^2, H = 1,000 cd/m^2 and I = 10,000 cd/m^2. (After Hills, B.L., *Lighting Res. Technol.*, 8, 11, 1976.)

of Dunbar (1938) and Moore (1952). Such information forms the background to the regulations governing signal lighting.

The two most widely used sources of standards relevant to vehicle signal lighting are the US FMVSS 108 and the ECE recommendations. Other countries follow one or other of these standards though with modifications to suit local circumstances. Over the last three decades, there has been convergence between the FMVSS and ECE standards, a process called harmonization. For many types of signal lamp, harmonization, although not complete, has resulted in sufficient overlap between standards for a manufacturer to be able to make one signal lamp that can meet both sets of requirements, something that is desirable for a global industry conscious of costs. Both the FMVSS and ECE standards cover the minimum and maximum luminous intensities that should be provided in different directions, the colour of the signal, the lit area of the lamp, the allowed positions of the lamp on the vehicle and, if flashing is called for, what the frequency of flashing should be.

The regulated aspects of vehicle signal lighting are measured when the lamps are new and clean, and it is always salutary to be reminded of reality. Schmidt-Clausen (1985) measured the luminous intensities of rear position lamps and stop lamps of new cars and cars in use. He found that the luminous intensities of rear signal lamps in use were half the minimum values required by regulations. Similarly, Cobb (1990) carried out a roadside survey of vehicle lighting in the United Kingdom, including rear signal lighting, and found that dirt typically reduced the luminous intensity of vehicle lighting by 30%–50%.

10.3.3 Front Position Lamps

In different parts of the world, front position lamps are known as parking lamps, sidelights, position lamps, standing lamps or city lights. The signal front position lamps are intended to convey is that of presence when stopped or parked. In America, front position lamps can be either white or yellow, but in countries that follow the ECE regulations, white is the only colour allowed. Front position lamps are required to remain illuminated once the vehicle forward lighting is lit. In many countries, it is illegal to drive a vehicle at night using front position lamps alone.

10.3.4 Rear Position Lamps

Rear position lamps, also known as tail lights or rear lights, are always red in colour. Their function is to indicate presence when moving or stopped. Rear position lamps have to be lit when the front position lamps are lit.

LED rear position lamps can be the cause of a visual illusion seen at night. The current to LED lamps is usually chopped at a high frequency to reduce the heating of the semiconductor junction. Given the high rise time of LEDs, this results in pulses of light output. When eye movements are limited, these pulses are not noticeable, but during a saccade, individual pulses may fall on different parts of the retina. When driving behind a vehicle equipped with LED rear lights at night, this can produce a perception of a series of red spots, called a phantom array. Roberts and Wilkins (2013) have shown that in darkness, such arrays can be seen at modulation frequencies in excess of 1 kHz. Whether or not this illusion has any impact on driver performance has yet to be determined but it can certainly be disturbing.

10.3.5 Side Marker Lamps

The basic function of side marker lamps is to indicate the presence of the vehicle to drivers at oblique angles to the direction of movement, a situation of importance at road junctions. In America, both side marker lamps and side retroreflectors are required, both being yellow at the front and red at the rear of the vehicle. The side marker lamps are connected so that they are lit whenever the front and rear position lamps are lit. The front yellow side marker lamps may also be wired so that the lamp on the relevant side flashes when a turn signal is activated, thereby adding another function.

In countries following the ECE regulations, side marker lamps are permitted rather than required. If they are installed, the side marker lamps are required to be visible over a wider range of angles than are those in America. Further, the side marker lamps must be continuously lit when the front and rear position lamps are lit, which means they cannot be connected to the turn signal. They must be yellow at the front and red at the rear, unless incorporated into a rear lamp cluster in which case the lamp can be red or yellow.

10.3.6 Retroreflectors

A retroreflector is a device that reflects light back from whence it came, over a wide range of angles of incidence. Retroreflectors come in a number of forms, the most common being the corner cube and the refractive/reflective combination. As its name suggests, the cube is an arrangement of three mutually perpendicular plane reflectors forming a corner, usually manufactured as a solid transparent cube. The corner cube relies on total internal reflection to redirect the light. The refractive/reflective combination has the reflective element coinciding with the image plane of the refractive element. A special case of this relevant to drivers is a transparent sphere that has a refractive index twice that of air. This will act as a retroreflector because the back surface of the sphere forms the image plane of the refracting front surface.

Retroreflectors are good for visibility when placed among diffusely reflecting surfaces, because they concentrate the reflected light in the direction from which it came, thereby giving the retroreflector a much higher luminance than the surroundings and hence a much higher luminance contrast when viewed from that direction. Of course, this is only true for an observer sitting close, in angular terms, to a small source of high luminous intensity, such as a driver in a vehicle with the headlamps on, at night.

The function of retroreflectors is to signal presence, even when there is no power on the vehicle. Both FMVSS- and ECE-based regulations require vehicles to have red retroreflectors at the rear. American regulations also require yellow front-facing retroreflectors. Some other countries require white front-facing retroreflectors.

10.3.7 Turn Lamps

So far, all the lamps considered are intended to make the vehicle more conspicuous and are permanently lit when the vehicle is moving after dark. Now, attention will be switched to signal lamps with a wider range of messages that are intermittently lit when the message is sent and which have to be visible both day and night. The first to be considered are turn lamps, also known as direction indicators, flashers or blinkers. These are lamps mounted at the front and rear corners and on the sides of the vehicle and are used to indicate to other drivers that the vehicle is about to turn or change lane. Regulations for turn lamps specify minimum and maximum luminous intensities, angles from which the signal should be visible, colour and flash rate, as well as feedback signals for the driver. Minimum luminous intensities on the optical axis of front turn lamps vary according to the separation of the turn lamp from the nearest headlamp. In America, the minimum of such luminous intensity is increased from 200 to 500 cd if the separation is less than 100 mm, the separation being measured as the distance between the optical centre of the turn lamp and the edge of the light-emitting area of the headlamp. In countries following the ECE recommendations, the minimum luminous intensity on the optical axis is increased from 175 to 400 cd when the separation of the edge of the turn lamp and the edge of the headlamp is not more than 20 mm. This increase in minimum turn signal luminous intensity when in close proximity to a headlamp is intended to overcome the masking effect of disability glare from the headlamp (Sivak et al., 2001).

Turn lamps flash at a rate of 1–2 Hz, with all the turn lamps on one side operating in phase. In countries following the ECE recommendations, front, rear and side turn lamps are yellow in colour, but the FMVSS regulations also allow the rear turn signal to be red, if desired. The side-mounted turn signal can take several different forms. In countries following the ECE recommendations, it takes the form of a dedicated turn signal. In America, the side marker lamp may also be used as a turn signal by making it flash in phase or anti-phase when the front and rear turn lamps are activated. Both ECE and FMVSS standards require that audiovisual feedback of the operation of turn lamps be given to the driver. This usually takes the form of a flashing light on the instrument panel together with an audible click at the same frequency. Failure of one or more of the turn lamps is indicated by an increased frequency of flashing and clicking.

Current practice in turn lamps has given rise to three questions about their effectiveness. The first concerns the use of red rather than yellow as a colour for the rear turn lamp in the United States. When stop lamps and rear position lamps are both red in colour and housed in the same cluster, it might be thought that the turn signal would be less conspicuous than one of a different colour, although the flashing of the signal may be sufficiently potent to negate the difference in colour, particularly as colour discrimination deteriorates in peripheral vision (Sivak et al., 1999). This may be why Taylor and Ng (1981) were unable to find any significant difference in the prevalence of rear-end collisions in Europe, where rear turn lamps are yellow, and in the United States, where rear turn lamps can be red or yellow.

The second question concerns the use of additional turn signals in side mirror housings. An analysis of the geometry between vehicles when one is about to pass the other in adjacent lanes indicates that such a mirror-mounted turn lamp can be seen over a wider range of relative positions by the driver of the overtaking vehicle than conventional side turn lamps because the latter are often obscured by the bodywork of the passing vehicle (Reed and Flannagan, 2003). Further, the mirror-mounted turn lamp is closer to the line of sight of the passing driver and hence more likely to be detected, a probability confirmed by Schumann et al. (2003). This is an important finding for one particular type of accident, lane change/merging. In this, the driver wishing to change lanes is unaware of the vehicle in the adjacent lane because it is the blind spot between the driver's peripheral vision and what can be seen in the side mirror (Wang and Knipling, 1994). As long as the lane changing vehicle is using the turn lamp, a greater ability to see it by the driver in the blind spot may allow that driver to take evasive action before contact. So far, attempts to test this hypothesis using crash data have failed to show a statistically significant effect (Sivak et al., 2006a), but this may be due to a lack of sensitivity caused by a small sample size rather than the absence of a real effect.

The third question concerns the choice between a clear lens and a coloured light source rather than a coloured lens and a white light source. This difference is trivial in darkness, but in daylight, it is not because then the greater amount of daylight that is reflected from the inside of the clear-lens turn lamp will increase the luminance on which the luminance produced by the operation of the light source is superimposed. The effect of this is to reduce the luminance increment when the turn lamp is lit. In addition, daylight entering and then exiting through a clear lens will desaturate the colour of the turn lamp when lit, although the colour difference between the lamp on and off will still be greater for the clear lens than for the coloured lens. Sullivan and Flannagan (2001) measured the reaction time to the onset of turn lamps using coloured and clear lenses in bright sunlight. The turn lamp with the coloured lens had a slightly shorter mean reaction time than those with clear lenses. Sivak et al. (2006b) measured the luminance contrasts for turn lamps on, with and without the sun, for a wide range of commercially available turn lamps. On average, the clear-lens turn lamps provided lower luminance contrasts for turn lamps on and off in sunlight than did the coloured-lens turn lamps. However, examination of the results shows that this is not inevitable. Clear-lens turn lamps can be designed that are resistant to strong sunlight, but it does require an awareness of the potential problem and attention to detail. Sivak et al. (2006b) also point out that the higher luminous intensities required for front turn lamps in close proximity to headlamps mean that clear-lens turn lamps of this type will be more resistant to confusion in bright sunlight.

10.3.8 Stop Lamps

Stop lamps, also known as brake lights, are mounted at the rear of the vehicle. They are red in colour and are lit when the driver applies pressure to the brake pedal. The function of the stop lamps is to inform drivers behind that the vehicle is decelerating, although it may not stop. An increase in luminous intensity is used to differentiate the stop lamp from the rear position lamp. Exactly how big a difference is required is open to question. Rockwell and Safford (1968) found that up to a luminous intensity ratio of 5.3 (stop lamp/rear position lamp), reaction time to the onset of the stop lamp was reduced, as was the likelihood of confusion between stop lamp and rear position lamp. In the United States, the minimum luminous intensity ratio (minimum for stop lamps/maximum for rear position lamps) for cars is in the range 4.4–4.7, while in those countries that follow the ECE recommendations, the minimum luminous intensity ratio is 5.0.

Visually, the problems associated with detecting the onset of a stop lamp are different by day and night. By day, detection can be difficult because daylight reflected from the stop lamp increases the luminance on which the luminance of the stop lamp is superimposed and hence reduces its luminance increment. In addition, some designers like to use rear lamp clusters that are of the same colour as the vehicle bodywork when the lamp is unlit. Such a body-coloured lamp may reduce or enhance the colour difference between the stop lamp and the surrounding area of the vehicle depending on the colour of the vehicle body. Chandra et al. (1992) measured reaction times to the onset of body-coloured stop lamps in simulated sunshine. Provided the vehicle body is not red, the onset of the stop lamp produces a change in both luminance and colour. Four chromatically neutral lamps varying from black to white when off and four body-coloured lamps when off were examined. They found that the smallest chromaticity shift occurred for the red body-coloured stop lamp. The smallest luminance shift occurred for the white body-coloured stop lamp. It was also shown that increasing the magnitudes of both luminance shifts and chromatic shifts is effective in decreasing reaction time, although the effects are small.

Another aspect to consider is the form of the stop lamp. Stop lamps can be part of a rear signal lamp cluster or separate. For both types, the stop lamp can vary in area and that area can have different aspect ratios. Sayer et al. (1996) found that both luminous intensity and aspect ratio influenced reaction time to the onset of a stop lamp. While luminous intensity was the major factor in determining reaction time, the effect of a low luminous intensity was particularly bad when the stop lamp had a high aspect ratio.

By night, the problem facing anyone wishing to detect the onset of a stop lamp is one of confusion because the rear position lamps will be lit, as well as, on occasion, the rear turn signal. Rear position lamps and stop lamps are all red in colour, and rear turn lamps may be in the United States. Further, rear turn lamps may have similar luminous intensities to stop lamps. Luoma et al. (2006) examined the influence of having rear stop lamps in a cluster or separate on rear-end crashes at night using data from Florida and North Carolina. They concluded that separate stop lamps tended to make rear-end collisions less likely, although the effect was complex and deserved further investigation. This finding is consistent with the work of Helliar-Symons and Irving (1981) who found that greater separation between stop lamps and rear fog lamps resulted in more accurate recognition of the onset of stop lamps and recommended a separation of at least 100 mm. Another approach to making stop lamps more noticeable is to use different colours for the rear turn lamps. Luoma et al. (1995) found that having yellow rear turn signals rather than red produced shorter reaction times to the onset of stop lamps, the reduction being about 110 ms.

While both separation and colour are used to enhance the difference between stop lamps, rear position lamps and rear turn lamps in some vehicles, there is one difference that is consistent across all cars and light trucks, namely, the number of lamps lit simultaneously. Rear position lamps occur in pairs. Rear turn lamps occur on one side only, unless used as hazard lamps, and flash rhythmically at 1–2 Hz. Stop lamps occur in a set of three, and while they may flash on and off according to the driver's pressure on the brake, the flashing is rarely rhythmic. The third stop lamp is the centre high-mounted stop light (CHMSL) or centre brake lamp, third brake lamp, eye-level brake lamp, safety brake lamp or high-level brake lamp. As its name implies, the CHMSL is mounted on or close to the centreline of the vehicle at a level above the left and right stop lamp. Different vehicle forms mean that the CHMSL is sometimes mounted at the roofline, sometimes at the top of the boot and at all points between.

The CHMSL was introduced with the twin objectives of making the signal that the vehicle ahead is braking more obvious to the vehicle immediately behind and of having a stop lamp that would be visible to vehicles separated from the braking vehicle by one or more vehicles between. Whether this second objective is met will depend on the nature of the vehicles between and the position of the CHMSL on the braking vehicle. A vehicle without windows at the rear, as is the case for most vans, does not allow a driver to see through the vehicle to the braking vehicle ahead. Even if a view through the vehicle ahead is possible, where the braking vehicle has a CHMSL at boot level, the CHMSL may not be visible. When the CHMSL is visible, there is some evidence that vehicles separated from the braking vehicle by another had shorter reaction times to the application of the brakes than when there was no

CHMSL on the braking vehicle (Crosley and Allen, 1966). If the use of CHMSLs leads to shorter reaction times to the onset of stop lamps, it seems reasonable to suppose that this would have an effect on the number of rear-end collisions. Rear-end collisions are one of the most frequent types of accidents, and although they are rarely fatal, they often cause injury, particularly to the neck. Kahane and Hertz (1998) have used accident data to estimate that the widespread use of CHMSLs is responsible for a 4.3% reduction in rear-end collisions.

One aspect of stop lamp design that is applicable to stop lamps in all positions, by day and night, is rise time. The rise time of a light source in a stop lamp is determined by the technology used to generate the light and the voltage applied. Incandescent light sources have a slow rise time, of the order of 200 ms, but LEDs potentially have a very fast rise time, of the order of nanoseconds. The effect of rise time in light output on reaction time to the onset of the stop lamp can be understood by considering the reaction time as the sum of two components, a visual reaction time and a non-visual reaction time. The visual reaction time is the time it takes for the light received from the stop lamp to be transformed to an electrical signal in the retina and transmitted up the optic nerve to the visual cortex. The non-visual component includes the time required for information received at the visual cortex to be processed and for neural signals to be sent to the muscles that make the response. Differences in rise time of light output for the stop lamp can be expected to influence the visual reaction time but not the non-visual reaction time. The effect of different rise times in light output can be estimated from the fact that to see the signal, a constant level of energy, that is, luminance integrated over time, is required to reach the retina (Teichner and Krebs, 1972). In other words, the visual reaction time is determined by the temporal summation properties of the visual system (see Section 2.4.4). Given a fixed maximum luminous intensity of the stop lamp, the shorter is the rise time of the light output, the shorter is the reaction time. This suggests that a fast-rise stop lamp, such as those using LEDs, would lead to shorter reaction times to onset, and this, in turn, might help diminish the number and severity of rear-end collisions (Sivak and Flannagan, 1993).

10.3.9 Hazard Flashers

Since the 1960s, turn lamps have been adapted to give a warning to other drivers that the vehicle is stopped in or near moving traffic, is disabled or is moving slowly. This signal is given by making all front, side and rear turn lamps flash in phase. The photometric conditions produced and the flash rate of the turn lamps are the same as when they are used to signal a turn.

10.3.10 Rear Fog Lamps

The function of rear fog lamps is, as the name implies, to increase the conspicuity of the vehicle in poor atmospheric conditions. Rear fog lamps are controlled manually by the driver, an action that sometimes leads to complaints of glare from drivers behind when the rear fog lamps are lit in only slightly degraded atmospheric conditions. When used, rear fog lamps can be installed as a single lamp on the driver's side of the vehicle or as a pair mounted symmetrically about the centre line. The case for the single rear fog lamp is that it is easily distinguished from stop lamps, while a pair of rear fog lights is not, even when a CHMSL is present (Akerboom et al., 1993). The disadvantage of the single rear fog lamp is that it does not provide a cue to distance for an approaching driver.

10.3.11 Reversing Lamps

The reversing lamp, also known as the back-up lamp, is unusual in rear lighting in that it is white in colour. This is because, when reversing, the back of the vehicle is functionally the front. The reversing lamp has two functions: to illuminate the road behind the vehicle so that the driver can see any obstructions and to alert other drivers and pedestrians about the direction of movement. The reversing lamp is automatically lit by placing the vehicle in reverse gear. One or two reversing lamps can be installed on a vehicle, but in the United States, if only one reversing lamp is used, it has to provide twice the minimum luminous intensity.

The problem with reversing lamps is not discriminating them from other rear signals; the different colour is enough to ensure that. The problem is in providing enough light to allow the driver of the reversing vehicle to see clearly. This problem is often exacerbated by the use of low-transmittance glazing in rear windows. Passenger cars in the United States are required to have glazing with a transmittance of at least 0.70. However, some common vehicle types, such as minivans and sports utility vehicles (SUVs), are classified as light trucks for which there are no limits on transmittance of the rear window. An option available for many minivans and SUVs is privacy glazing for the windows behind the driver. The transmittance of privacy glazing is of the order of 0.18. The installation of privacy glazing has consequences. Freedman et al. (1993) found a decreased probability of detection of children and debris with lower-transmittance glazing when preparing to reverse. Sayer et al. (2001) used a US database to examine the impact of lighting conditions, driver age and vehicle type on reversing accidents as a proportion of all accidents. The database, the General Estimates System, contains a nationally representative sample of police-reported accidents. Table 10.2 shows the percentage of reversing

TABLE 10.2
Percentages of Reversing Accidents and Total Accidents for Cars, Minivans and SUVs for Drivers Less than 66 Years of Age Who Had Not Been Drinking

Vehicle Type	Reversing Accidents (%)	All Accidents (%)
Cars	82.1	88.3
Minivans/SUVs*	17.9	11.7

Source: Sayer, J.R. et al., *The Effects of Rear-Window Transmittance and Back-Up Lamp Intensity on Backing Behavior*, Report UMTRI-2001-6, University of Michigan Transportation Research Institute, Ann Arbor, MI, 2001.

Note: Statistically significant differences are marked with an asterisk.

TABLE 10.3
Percentages of Reversing Accidents and Total Accidents for Minivans and SUVs by Ambient Illumination, for Drivers Less than 66 Years of Age Who Had Not Been Drinking

Ambient Illumination	Reversing Accidents (%)	All Accidents (%)
Daylight	66.6	76.1
Dark	7.2	7.6
Dark/lighted	15.4	11.5
Dawn/dusk*	9.3	3.7
Unknown	1.5	1.2

Source: Sayer, J.R. et al., *The Effects of Rear-Window Transmittance and Back-Up Lamp Intensity on Backing Behavior*, Report UMTRI-2001-6, University of Michigan Transportation Research Institute, Ann Arbor, MI, 2001.

Note: Statistically significant differences are marked with an asterisk.

accidents and all accidents for cars, minivans and SUVs involving drivers less than 66 years of age, who had not been drinking. Minivans and SUVs are involved in a higher percentage of reversing accidents than would be expected from all accidents. Table 10.3 shows the percentage of reversing accidents and all accidents for minivans and SUVs in different ambient lighting conditions, involving drivers less than 66 years of age who had not been drinking. The percentage of reversing accidents is what would be expected from the overall accident distribution for daylight, dark but lighted and after dark conditions, but for dawn and dusk conditions, the percentage of reversing accidents is statistically significantly greater than would be expected. Taken together, these results suggest that in dark conditions, drivers reversing are careful because they are aware that they cannot see well. In daylight, there is no problem in seeing well, but in dawn and dusk conditions, and possibly in dark but lighted conditions, drivers of minivans and SUVs overestimate how well they can see when reversing. There are a number of possible solutions to this problem, among them being the banning of low-transmittance glazing, an increase in luminous intensity for reversing lamps where low-transmittance glazing is used and the use of sensors to detect obstacles behind the vehicle when reversing. The last of these options is becoming increasingly common in vehicles.

10.3.12 Daytime Running Lamps

Daytime running lamps are lamps positioned at the front of the vehicle and used during the day to increase the conspicuity of the vehicle. Daytime running lights can take many different forms, some using multiple LEDs arranged so as to make the vehicle instantly identifiable as well as conspicuous. But why should a vehicle need to have its conspicuity increased in daytime when the visibility of everything on the road should be high? There are two answers to this question. The first is the sad fact that about half of fatal vehicle accidents occur in daytime, so there is certainly a problem (Bergkvist, 2001). The second is that the most basic error of drivers is late detection (Rumar, 1990). Increasing conspicuity should enable a driver to detect other vehicles earlier. But why does late detection occur so frequently? The answer to this question involves both cognitive and visual factors (Hughes and Cole, 1984; Rumar, 1990). The cognitive factor is a matter of expectation and hence the allocation of limited attention. If attention is given to the wrong part of the visual world, late detection of an approaching vehicle is likely. Conspicuity is essentially a measure of the ability to attract attention. The visual factor is a matter of a weak stimulus, particularly in the peripheral visual field. A vehicle approaching or being approached head-on at speed causes little change in the retinal image which may make it difficult to detect until too late. Daytime running lamps are an attempt to attract attention to the other vehicle and hence to get drivers to use foveal vision to examine the other vehicle's movement in detail.

From the earlier discussion, it would seem that daytime running lamps are an obvious means to reduce daytime accidents, but that may not be so. Daytime running lamps have potential drawbacks as well. Concerns have been expressed about the possibility that daytime running lamps may cause glare, may mask turn signals and may reduce the conspicuity of vehicles who already use them, such as motorcycles, or who do not have them, such as bicycles (Rumar, 2003). The extent to which daytime running lamps might cause glare will depend on the ambient illuminance. Studies of discomfort glare received through rearview mirrors show that for a low ambient illuminance of 700 lx, a luminous intensity of 1,000 cd is just permissible, but for a high ambient illuminance of 90,000 lx, a luminous intensity of 5,000 cd is acceptable (Kirkpatrick et al., 1987; SAE, 1990). The FMVSS regulations applicable to daytime running lamps allow luminous intensities that seem likely to cause discomfort. As for masking of turn signals, SAE (1990) found masking when the daytime running lamps had a luminous intensity of 5000 cd and higher and were observed from a short distance, but at longer distances, masking could occur for luminous intensities of 1000 cd, especially if the separation between the turn signal and the daytime running lamp was small, findings that are consistent with what is known about disability glare (see Section 10.2.5). Again, the FMVSS regulations applicable to daytime running lamps allow luminous intensities that are capable of masking turn signals.

In response to these concerns, it would seem to be a simple matter to reduce the maximum luminous intensity allowed, but there is a problem with this. It is simply that the higher is the ambient illuminance, the greater is the luminous intensity required for daytime running lamps to increase the conspicuity of the vehicle (Rumar, 2003). This observation suggests that daytime running lamps, as currently regulated, should have a greater effect on conspicuity and hence accidents in countries at high latitudes where the ambient illuminance is low more frequently and the sun is low in the sky for longer (Koornstra, 1993). Elvik (1996) has examined this possibility and concluded that it is correct.

There is also concern about the relative conspicuity of different vehicle types. This concern arises because if having daytime running lamps makes one vehicle more conspicuous and the available attention is limited, then another vehicle without daytime running lamps should become less conspicuous. Attwood (1979) has shown that it is more difficult to detect a car without daytime running lamps when it is between two cars that have them than when none of the cars have them. The inverse of this situation is a particular concern for motorcyclists who, of all road users, are the most likely to be killed or injured. Even where daytime running lamps are not required, motorcyclists are encouraged to drive with headlamps on during the day to increase their conspicuity, something that is very desirable given the small frontal area of a motorcycle and the consequent difficulty in detecting presence and estimating distance and speed. Wells et al. (2004) have shown that motorcyclists who use headlamps by day have a 27% lower risk of being killed or injured than those who do not. With regard to daytime running lamps, the motorcyclists' concern is that if every vehicle were to have daytime running lamps, the conspicuity of motorcycles would be reduced. Whether or not such a reduction would matter is almost certainly related to traffic density and attentional capacity. Where there are only a few vehicles on the road, there should be enough attentional capacity for a driver to examine all of them, starting with those that are using headlamps or daytime running lamps. Where there are many vehicles on the road, there may not be enough attentional capacity to examine all the vehicles. If daytime running lamps are widespread and motorcycles use their headlamps by day, the only advantage motorcycles have is the greater luminous intensity of headlamps over daytime running lamps. This argument implies that motorcyclists' concerns about reduced conspicuity following the widespread introduction of daytime running lamps are justified for heavy traffic. One possibility would be to maintain the conspicuity advantage of motorcycles above cars by making their headlamps flash or pulse by day.

As for other road users without daytime running lamps such as cyclists, Cobb (1992) examined the conspicuity of bicycles near cars equipped with daytime running lamps of different luminous intensities. He found that daytime running lamps increased the conspicuity of cars but did not reduce the conspicuity of bicycles until the luminous intensity of the daytime running lamps was very high, presumably high enough to produce masking by disability glare. This unexpected finding may simply indicate a halo effect around daytime running lamps. If the daytime running lamps attract attention to the car and the bicycle is close to the car, the retinal image of the bicycle is closer to the fovea and is more likely to be detected. However, if the bicycle is some way away from the car, directing attention to the car may reduce the chances of the bicycle being detected. A similar argument may apply to pedestrians in the road. Daytime running lamps do not make pedestrians more visible to drivers, so the presence of daytime running lamps on other vehicles may attract drivers' attention away from pedestrians, particularly in heavy traffic. Fortunately, this disadvantage may be more than offset by making a vehicle with daytime running lamps easier to detect by the pedestrian. Thompson (2003) found that the largest accident reduction associated with the use of daytime running lamps concerned collisions with pedestrians, particularly children.

These observations indicate that introducing a legal requirement for daytime running lamps is a matter of balance between the positive effect of enhanced conspicuity for some and the negative effects of glare and reduced conspicuity for others. A legal requirement for daytime running lamps has been introduced in a number of countries and the consequences studied. Elvik (1996) has carried out a meta-analysis of 17 such studies and concludes that the beneficial effects of daytime running lamps are robust. He further concludes that the use of daytime running lamps on cars reduces the number of multiparty daytime accidents by about 10%–15% for vehicles having daytime running lamps and reduces the total number of multiparty daytime accidents by about 3%–12%. He also states that there is no evidence that the use of daytime running lamps affects any type of accident other than multiparty accidents. Such reductions are somewhat greater than indicated by Farmer and Williams (2002) who found that, in the United States, vehicles with automatic daytime running lamps were involved in 3.2% fewer multiparty accidents than those without. Also for the United States, Sivak and Schoettle (2011) claim that in 2009, the presence of daytime running lights reduced fatal two-vehicle head-on crashes by 8% in daylight and 28% at dawn and dusk. Despite this variability, there can be little doubt that the large-scale use of daytime running lamps is advantageous to traffic safety, particularly in high-latitude countries.

10.3.13 Emergency Vehicle Lighting

One final form of signal lighting that needs to be considered is that used on emergency vehicles such as ambulances and police vehicles. These are often fitted with flashing lights of a specific colour to identify the purpose of the vehicle. Bullough et al. (2001a) measured how quickly drivers following a snow plough at night, in snow, could detect that the speed of the snow plough had changed so that they were closing on it. They found that when the rear of the snow plough was fitted with two vertical, constantly illuminated LED bars, the change in speed of the snow plough could be detected 20% faster than when it was fitted with two flashing amber lights. Flashing marker lights are undeniably effective in attracting attention to the vehicle, particularly during daytime when there is much other competing visual information, but at night, flashing lights can make it more difficult to estimate relative speed, distance and closure (Croft, 1971; Hanscom and Pain, 1990). Anyone who has come across an accident, on an unlit road, at night, being attended by three police vehicles, one ambulance and one fire engine, all equipped with flashing lights, has experienced the difficulty in extracting visual information. There is no doubt that the scene should be approached with caution, but what is expected of the approaching driver is unclear. This is because the flashing lights are often the only illumination of the scene and every flashing light produces glare and operates at a different phase, so the scene is continually changing in appearance. One approach to solving this problem would be to limit the number of flashing lights on any emergency vehicle and to reduce the percentage modulation of each flashing light. It seems likely that one or two flashing lights visible from all angles would be sufficient to attract attention to a vehicle at night and that adding more flashing lights will do little other than cause confusion.

10.3.14 Improving Vehicle Signal Lighting

In many ways, the development of vehicle signal lighting has been characterized by the piecemeal addition and modification of signals as the need arises. However, there have been a number of suggestions made for systematically improving the effectiveness of vehicle signal lamps. These suggestions have varied from those attempting to improve existing signal lamps by increasing visibility and removing ambiguity, through those that aim to increase the amount and type of information conveyed by the signal lamp to those that combine signal lamps with sensors to make the signal more responsive to prevailing conditions.

In the first group comes the suggestion by Mortimer (1977) that rear signal lamps should be colour coded for function. The idea was that by colour coding, the speed of response to the signal would be increased. Another suggestion was to change the location and number of all signal lamps so as to minimize the probability of them being hidden by parts of other vehicles. For heavy trucks, this is already common, with many having additional high-level rear position and stop lamps as well as multiple side marker lamps. A similar approach could readily be implemented in small trucks and vans. Even if this were unacceptable, it would be a good idea for the CHMSL in cars really to be mounted high up on the vehicle and not somewhere convenient. Yet another proposal made by several authors is for turn and stop signal lamps to have two levels of light output, one for use by day and one by night (Moore and Rumar, 1999). The idea behind this proposal is that the ambient lighting is very different by day and night, yet current turn and stop lamps have a fixed luminous intensity distribution which is inevitably a compromise between providing a high enough luminous intensity for the lamp to be conspicuous by day without causing glare at night. By having different luminous intensities by day and night, the luminous intensity could be increased by day and decreased by night so that conspicuity is increased by day and glare is reduced at night. Finally, Huhn et al. (1997) have suggested that hazard flashers would be more easily discriminated from turn signals by having these two signals flash at different frequencies. Despite the logic of these proposals and the ease with which they could be implemented, most of them have fallen on stony ground.

The second group reflects the desire to provide more information by signal lamps. One example that has already attracted attention is the stop lamp. At the moment, the activation of the stop lamp simply tells drivers behind that the brakes have been applied in the vehicle ahead but nothing about how strongly they have been applied. Horowitz (1994) suggests the use of a combination of flashing and colours to discriminate between deceleration without breaking, sudden accelerator release, anti-lock braking system activated and braking at low speeds or stopped. Vehicles with stop lamps that have a normal appearance when the brakes are applied normally but change appearance when the driver attempts an emergency stop have also been tested. The change in appearance involves either an increased brightness, an increase in lit area or flashing. Unfortunately, studies of the use of a signal indicating sharp deceleration have given only limited support to its value for enhancing traffic safety (Rutley and Mace, 1969; Voevodsky, 1974; Mortimer, 1981).

Another suggestion is to arrange signal lamps so as to make it easier to identify the type of vehicle at night and to estimate the rate of closure. Identifying the type of vehicle is useful because different vehicles have different dynamics. Estimating the rate of closure is valuable for avoiding rear-end collisions. One approach to identifying the type of vehicle is to use retroreflective material to outline the vehicle. Support for this approach comes from the finding that contour lighting of heavy trucks is effective in reducing collisions at night (Schmidt-Clausen and Finsterer, 1989). As for estimating the rate of closure at night, the primary cue used is the angular separation of the rear position lamps of the vehicle ahead, so much so that Janssen et al. (1976) suggested that the separation between rear position lamps should be standardized and set as wide as possible.

The third group, integration with sensors, is already evident in newer vehicles. For example, many cars now have a sensor to activate and deactivate headlamps and position lamps according to the ambient illuminance. It is not too difficult to see a similar sensor being used to adjust the luminous intensity of rear fog lamps and of daytime running lamps so as to maintain a constant level of conspicuity in different ambient conditions. Another role for sensors is to ensure that the correct signal is sent every time it is required. This would overcome the problem of drivers turning or changing lanes without signalling or carrying on straight ahead while signalling a turn (Ponziani, 2006). It should be possible to develop a system whereby any attempt to change lane or turn without signalling would trigger the relevant turn signal, although this would still give little notice to nearby vehicles. More useful would be a more sensitive system to automatically cancel a turn signal after completion of the manoeuvre. Finally, there is the possibility of communication between vehicles. For example, it should be possible to use a proximity sensor so that the approach of another vehicle too close behind causes the rear position lamps to be pulsed.

Clearly, there is no shortage of ideas for improving the rather ambiguous and confusing system that currently constitutes vehicle signal lighting (Bullough et al., 2007). What is required to get some of these proposals implemented is evidence that the proposed changes are effective in changing driver behaviour in a desirable direction, that the new equipment is reliable in use and, when installed on a large scale, that the new equipment does indeed reduce accidents and injuries. This is a rational approach to developing better vehicle signal lighting. But rational development takes time and money. Until these resources are available, it is likely that vehicle signal lighting will continue to develop in an *ad hoc* manner, driven by whatever the market tells the vehicle manufacturer is most attractive to potential customers.

10.4 ROAD LIGHTING

Road lighting designed specifically for enhancing the safety of the driver began to appear in the 1930s. Three factors converged to make road lighting possible and desirable at this time. The first was the availability of the necessary technologies in the form of an extensive electricity distribution network together with suitable light sources and luminaires. The second was the establishment of official systems for regulating the design and use of vehicles and the control of traffic. The third was the growth in the number of vehicles on the roads and the speeds those vehicles could sustain. Despite this convergence, the growth in road lighting was slow, and it was not until the 1960s that road lighting became an important component of any road scheme. This is still the situation but over the last few years, authorities looking to reduce public expenditure have found road lighting an easy target, so much so that some road lighting is switched off or dimmed during the hours when traffic densities are low (ILP, 2005).

10.4.1 Technology

The technology used for road lighting involves decisions on light sources and luminaires arranged in different ways and controlled by different means. Over the decades, the main light sources used for road lighting have ranged through mercury vapour, low-pressure sodium (LPS), high-pressure sodium (HPS) and metal halide (MH) (see Section 1.7.3). The light source characteristics most important for road lighting are cost, for obvious reasons; luminous efficacy because that affects energy costs; lamp life because that affects maintenance costs; and colour rendering because that affects the appearance of people and their surroundings. Different countries have struck different balances between these factors. In the United Kingdom, for many years, the light source most widely used for road lighting was LPS, most emphasis being placed on luminous efficacy and little on colour rendering. In Eastern Europe, mercury vapour is still common. In Western Europe and the United States, HPS is the light source of choice, although MH is gaining ground. In all these areas, there is rising interest in the use of LEDs because of their long life, ease of control and the possibility of manipulating the light spectrum to maximize the effective light output (see Section 10.4.3).

The luminaires used for road lighting can be characterized on several different dimensions. One of the most variable is the luminous intensity distribution. There are a large number of luminous intensity distributions available, some symmetrical and some asymmetrical. Further, many luminaires allow for on-site adjustments in light source position within the luminaire to modify the luminous intensity distribution. Different light distributions are necessary because roads of different widths and layouts require different light distributions if the light is to be directed onto the road surface and not wasted. The exception to this concern is high-mast lighting where the luminaires are mounted 30 m or more above the ground. High-mast lighting is used for lighting complex road junctions where the waste inherent in illuminating large areas between roads is more than offset by the cost savings produced by minimizing the number of columns and simplifying the electricity distribution network.

Other important characteristics of road lighting luminaires are the light output ratio, the protection provided against the ingress of dirt and moisture and the physical size. The luminaire light output ratio quantifies the proportion of light emitted by the light source that gets out of the luminaire. Light output ratios for road lighting luminaires tend to be about 0.8. The level of ingress protection is given by the IP number (SLL, 2009). Typically, road lighting luminaires are IP65, meaning they are strongly protected against the ingress of dust and driving rain. This implies that the interior of the luminaire should remain clean, although the outside will still require regular cleaning if a marked deterioration in light output is to be avoided. As for physical size, this is relevant to the amount of leverage applied to a lighting column in high winds. The smaller the physical size of the luminaire and the more aerodynamic its shape, the less will be the leverage.

Most road lighting installations use columns to carry the luminaire or luminaires, although some installations use wire suspensions between buildings to light urban streets or catenary suspensions along traffic routes. Columns vary in height and the materials used. Column heights above ground level typically range from 3.5 to 14 m. Materials are usually aluminium or steel, although concrete was used in the past and plastic composites are of current interest. In rural areas where the electricity network uses overhead distribution, the poles carrying the electricity lines are often used for mounting the luminaires, regardless of the distortions this imposes on the lighting conditions achieved.

The control of road lighting is usually based either on time or on the amount of daylight available and is applied to individual luminaires or to groups of luminaires. In the past, most road lighting was controlled by time switches to be on from half an hour after sunset to half an hour before sunrise, although enthusiasm for energy savings meant that some installations were partially or totally switched off at midnight. However, the use of time switches makes it difficult to deal with unexpected meteorological conditions. Today, the most common control system is based on a photoelectric cell, this being used to detect the amount of daylight available and thus to ensure that the road lighting is only used when necessary. In the future, this relatively simple control system is likely to become much more sophisticated. Developments in light source technology and electronic control gear are making dimming of discharge and LED light sources feasible. Further, developments in computer networking using mains signalling and wireless communication are making it possible to control many individual luminaires from a remote site and hence to manage their operation. These technical advances are consistent with the current interest in dimming road lighting according to traffic flow and weather conditions (ILP, 2005; Guo et al., 2007).

10.4.2 Standards

Road lighting standards vary in detail from country to country, but they do have some common features. One is the division of the road network into different classes, according to the type of users and the road geometry (Schreuder, 1998; Boyce, 2009; CIE, 2010c). Road lighting standards in the United States vary from state to state, but many states have adopted the IESNA (2005a) recommended practice as a basis for their standards. This document offers three different metrics for the design of road lighting: the illuminance on the road, the luminance of the road as seen by the driver and the small target visibility for the driver. All are minima that should be maintained over the life of the installation. The illuminance recommendations range from a mean illuminance on the road surface of 3–12 lx. The actual illuminance recommended depends on the road type, typical traffic density, speed limits and the risk of conflict with pedestrians. There are two features of these recommendations worth noting. The first is that the highest illuminances are recommended not for freeways, where traffic speeds are likely to be highest and access is limited, but for major roads with high pedestrian conflict areas. The second is that the recommended illuminances for any class of road decrease as the pedestrian conflict class changes from high to low. The recommendations for minimum maintained road surface luminance follow a similar pattern, ranging from 0.3 to 1.2 cd/m^2. As for small target visibility, this is a metric designed to quantify the effect of road lighting on something closer to its ultimate purpose than conventional photometric measures. However, it is not used outside the United States, and only rarely there, so it will not be considered further here (see Boyce [2009] for a discussion on its value).

Both the recommended illuminance on the road and the road surface luminance are averages, so both also have recommended minimum uniformity ratios. For both, the minimum uniformity ratios, defined as ratio of the minimum to the average, range from 0.17 to 0.33, the uniformity becoming less as the traffic densities and the level of pedestrian conflict decrease.

One other aspect of road lighting that needs to be controlled is disability glare from the road lighting luminaires. In IESNA (2005a), this is dealt with by recommending a maximum veiling luminance ratio which is defined as the ratio of the equivalent veiling luminance to the average road surface luminance (see Section 5.4.2.1 for a formula for calculating equivalent veiling luminance). For freeways, expressways and major roads, regardless of the pedestrian conflict class, the maximum veiling luminance ratio is 0.3. For collector and local roads, regardless of the pedestrian conflict class, the maximum veiling luminance ratio is 0.4.

The road lighting recommendations used in the United Kingdom (BSI, 2003, 2013) identify three distinct situations: traffic routes where vehicles are dominant, conflict areas where streams of vehicles intersect with each other or with pedestrians and cyclists and residential roads where the lighting is primarily intended for pedestrians and cyclists. Traffic routes are again divided into different classes. The different classes are based on the road type, average daily traffic flow, speed limits, the frequency of conflict areas, any parking restrictions and the presence of pedestrians. The photometric conditions required are specified as minimum maintained average road surface luminance and overall and longitudinal luminance uniformity. The overall luminance uniformity is the ratio of the lowest to the average road surface luminance. The longitudinal luminance uniformity is the ratio of the lowest to the highest luminance found at test points on a line along the centre of a single lane. The average road surface luminance covers a range of 0.3–2.0 cd/m^2. The overall luminance uniformity and the longitudinal luminance uniformity cover ranges of 0.35–0.40 and 0.40–0.70, respectively. The highest average road surface luminance and highest luminance uniformities are recommended for motorways that have the highest speeds and highest traffic density even though pedestrians are excluded from such roads. As for disability glare, this is limited by the use of a maximum percentage threshold increment (TI). The percentage TI can be obtained from the following formula:

$$\mathrm{TI} = 65\left(\frac{L_v}{L^{0.8}}\right)$$

where

L_v is the equivalent veiling luminance (cd/m^2)

L is the average road surface luminance (cd/m^2)

The maximum allowed TI ranges from 10% to 15%, the lower value being recommended for roads with high traffic densities and speeds.

As well as differences in metrics and road classes, there are some other interesting differences between the road lighting recommendations used in the

United Kingdom and the United States. For the average road surface luminance, the UK recommendations cover a wider range (0.3–2.0 cd/m^2) than the US recommendations (0.3–1.2 cd/m^2). In fact, the average road surface luminance for freeways in the United States (0.6 cd/m^2) is less than a third of the average road surface luminance for motorways recommended in the United Kingdom (2 cd/m^2). Another area in which the UK standards are higher is in the illuminances for junctions. In the US recommendations, the recommended maintained average illuminances range from 8 to 34 lx, but for conflict areas in the United Kingdom, which include junctions, the illuminance range is 7.5–50 lx. Another metric showing a difference is the overall luminance uniformity. The UK and US recommendations require the overall luminance uniformity for traffic routes to be 0.35–0.40 for the former and 0.17–0.33 for the latter. What these differences should mean is that the UK recommendations will lead to more uniform lighting of roads than the recommendations used in the United States. Unfortunately, this may not be what happens in practice because road surface luminances are likely to vary from site to site (Hargroves, 1981). This is because the actual road surface luminance will depend on the reflection characteristics of the road surface. These can change with the materials used to construct the road and over time as the road wears (Dumont and Paumier, 2007). To avoid these problems, road lighting is designed using a representative road surface with assumed reflection properties, which may or may not be truly representative of the actual road.

10.4.3 Spectral Effects

One aspect of road lighting that is not evident in standards and recommendations is the effect of light spectrum. The perceived colour of road lighting varies greatly from the monochromatic yellow of LPS, through the orange of HPS, to the white of MH and LED light sources. Several studies have been made of the effectiveness of these light sources for making largely achromatic objects on the carriageway visible, without any clear conclusions, suggesting that any effects are small (Eastman and McNelis, 1963; de Boer, 1974; Buck et al., 1975). One common feature of these evaluations is that all the measurements were taken fixating the object, that is, the retinal image fell on the fovea. More recent measurements of the effect of light spectrum on the detection of off-axis targets suggest that there is a significant effect of light colour relevant to road lighting. Specifically, He et al. (1997) carried out a laboratory experiment in which HPS and MH light sources were compared for their effects on the reaction time to the onset of a 2° diameter disc with the centre either on-axis or 15° off-axis, for a range of photopic luminances from 0.003 to 10 cd/m^2. The luminance contrast of the disc against the background was constant at 0.7. The same light source was used to produce both the background luminance and the stimulus, so there was no colour difference between the stimulus and its background. Figure 10.23 shows the median reaction time to the onset of the stimulus, on-axis and off-axis, for a range of photopic luminances, for two practiced observers. From Figure 10.23, it is evident that reaction time increases as photopic luminance decreases from the photopic to the mesopic state, for both on-axis and off-axis detection. There is no difference between the two light sources in the change of reaction time with luminance

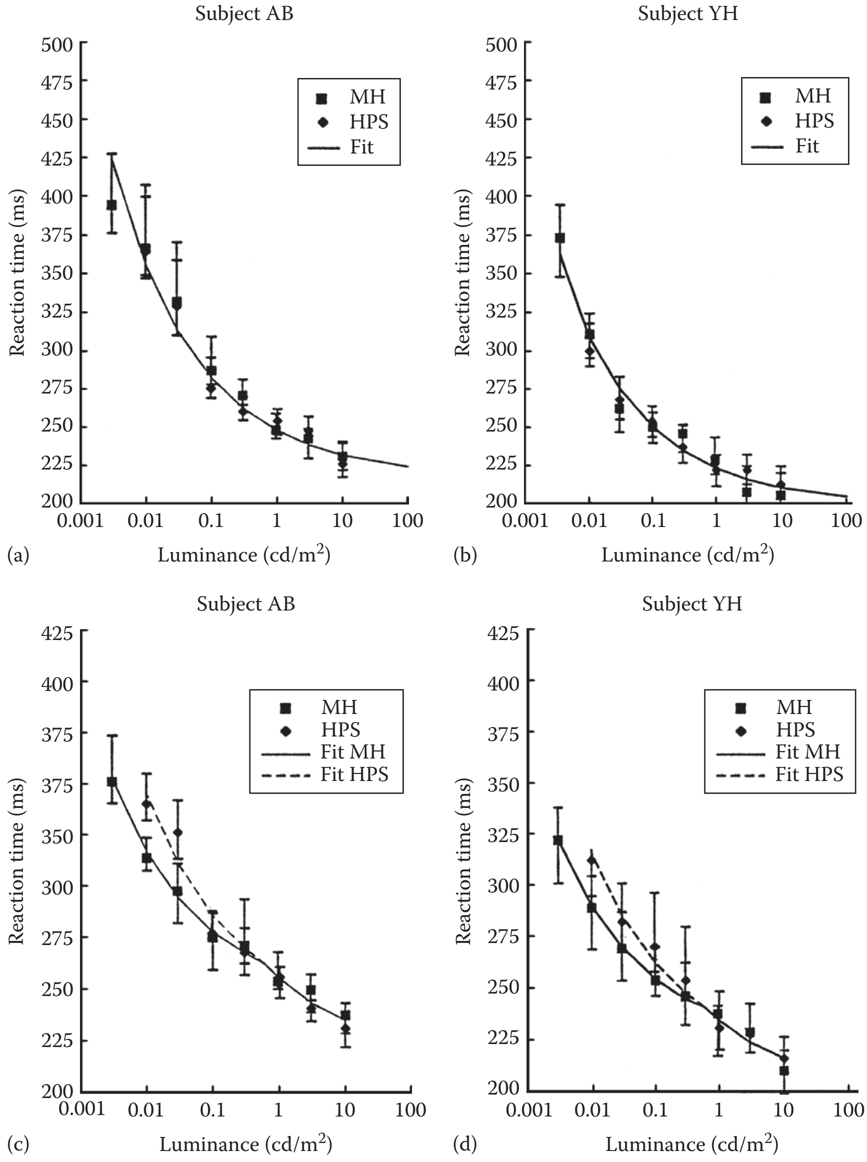


FIGURE 10.23 Median reaction times (ms), and the associated interquartile ranges, to the onset of a 2°, high-contrast target seen either (a and b) on-axis or (c and d) 15° off-axis and illuminated using either HPS or MH light sources, for photopic luminances in the range 0.003–10 cd/m². (After He, Y. et al., *J. Illum. Eng. Soc.*, 26, 125, 1997.)

for on-axis detection, but for off-axis detection, the reaction times for the two light sources begin to diverge as vision enters the mesopic region. Specifically, the reaction time is shorter for the MH light source at the same photopic luminance, and the magnitude of the divergence between the two sources increases as the photopic luminance decreases.

These findings can be explained by the structure of the human visual system. The fovea, which is what is used for on-axis vision, is dominated by cone photoreceptors, so its spectral sensitivity does not change as adaptation luminance decreases until the scotopic state is reached, at which point the fovea is effectively blind. The rest of the retina contains both cone and rod photoreceptors. In the photopic state, the cones are dominant, but as the mesopic state is reached, the rods begin to have an impact on spectral sensitivity until in the scotopic state, the rods are completely dominant. Given the different balances between rod and cone photoreceptors in different parts of the retina and under different amounts of light, it should not be surprising that the MH light source produces shorter reaction times for off-axis detection than the HPS in the mesopic range because it is better matched to the rod spectral sensitivity. It is also evident why there is no difference between the two light sources for on-axis reaction times.

Lewis (1999) has obtained similar results. Figure 10.24 shows the mean reaction time to correctly identify the vertical or horizontal orientation of a large, achromatic, high-contrast, 13° by 10° grating, where the grating was lit by one of five different light sources, LPS, HPS, mercury vapour, incandescent and MH, plotted against the photopic luminance. As long as the visual system is in the photopic range, that is, above about 3 cd/m^2, there is no difference between the different light sources provided they produce the same photopic luminance. However, when the visual system is in the mesopic state, that is, below about 3 cd/m^2, the different light sources produce different reaction times, the light sources that better stimulate the rod photoreceptors (incandescent, mercury vapour and MH) giving shorter reaction times than the light sources that stimulate the rod photoreceptor less (LPS and HPS).

Such measurements of the time to detect the onset of abstract targets under different light sources may seem irrelevant to the task of driving, but in fact, driving often requires the visual system to extract information from the peripheral visual field. Lewis (1999) verified that the spectral power distribution of a light source does have an effect on the time taken to extract information of relevance to driving, by repeating

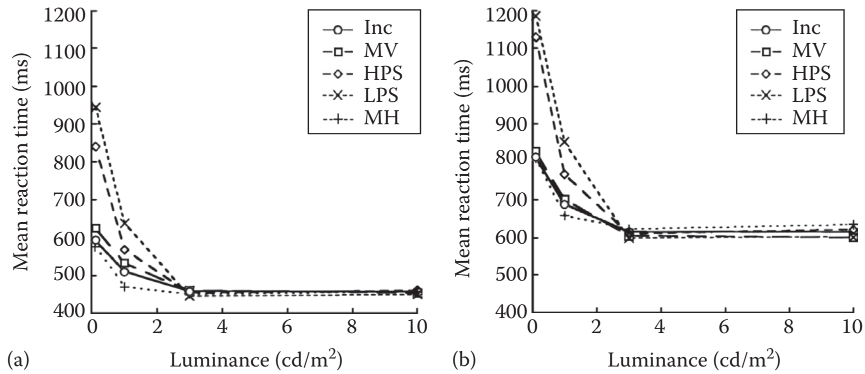


FIGURE 10.24 Mean reaction time (ms) to correctly identify the vertical or horizontal orientation of (a) a grating and (b) the direction a pedestrian located adjacent to a roadway is facing, plotted against the photopic luminance (cd/m^2) produced by five different light sources (Inc, incandescent; MV, mercury vapour; HPS, high-pressure sodium; LPS, low-pressure sodium; MH, metal halide). (After Lewis, A.L., *J. Illum. Eng. Soc.*, 28, 37, 1999.)

the experiment described above but replacing the gratings with a transparency of a female pedestrian standing at the right side of a roadway in the presence of trees and a wooden fence. In one transparency, the woman was facing towards the road; in the other, she was facing away from the road. The observer's task was to identify which way the woman was facing. Figure 10.24 also shows the mean reaction times for this task, under the different light sources, over a range of photopic luminances. Again, there is no difference between the light sources as long as the visual system is in the photopic state, but once it reaches the mesopic state, the light sources that more effectively stimulate the rod photoreceptors show shorter reaction times.

Another approach to evaluating the effect of light spectrum in mesopic conditions measured the probability of detecting the presence of a target off-axis. Akashi and Rea (2002) had people drive a car along a short road while measuring their reaction time to the onset of targets 15° and 23° off-axis. The lighting of the road and the area around it was provided by either HPS or MH road lighting, adjusted to give the same amount and distribution of light on the road and seen with and without the vehicle's halogen headlamps. There was a statistically significant difference between the HPS and MH lighting conditions. Specifically, the mean reaction time to the onset of the targets was shorter for the MH road lighting than for the HPS road lighting at both angular eccentricities (Figure 10.25).

Given the results discussed earlier, there can be little doubt that light spectrum is a factor in determining off-axis visual performance, but how important is it? It could be argued that the increase in reaction times in the luminance range of interest is small and would make little difference to traffic safety. For example, an increase of 100 ms in reaction time would mean a vehicle moving at 80 km/h (50 mph) would

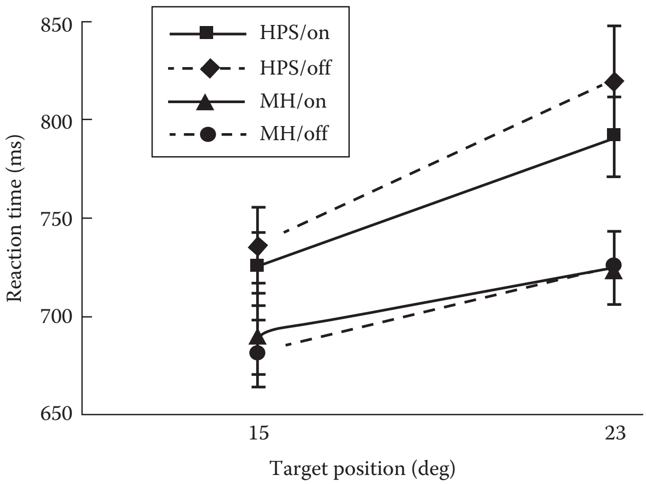


FIGURE 10.25 Mean reaction times (ms) (and the associated standard errors of the mean) to the onset of a target at 15° and 23° off-axis while driving, with HPS and MH road lighting, and with halogen headlights turned on and off. The road lighting using the two light sources was adjusted to give similar illuminances and light distributions. The rectangular target subtended 3.97×10^{-4} steradians for the 15° off-axis position and 3.60×10^{-4} steradians for 23° off-axis position. Both targets had a luminance contrast against the background of 2.77. (After Akashi, Y. and Rea, M.S., *J. Illum. Eng. Soc.*, 31, 85, 2002.)

travel only 2.2 m further because of the longer reaction time. Fortunately for those committed to the importance of light source spectrum, there is some evidence that longer reaction times are associated with more missed events. Rea et al. (1997) measured observers' responses to a change of high-contrast character on a changeable message sign located 15° off-axis. The setting was a roadway lit by either HPS or MH light sources so as to give an average road surface luminance of 0.2 cd/m^2. An effective average road surface luminance of 0.02 cd/m^2 was achieved by asking the observers to wear glasses with a transmittance of 0.1. Figure 10.26 shows the

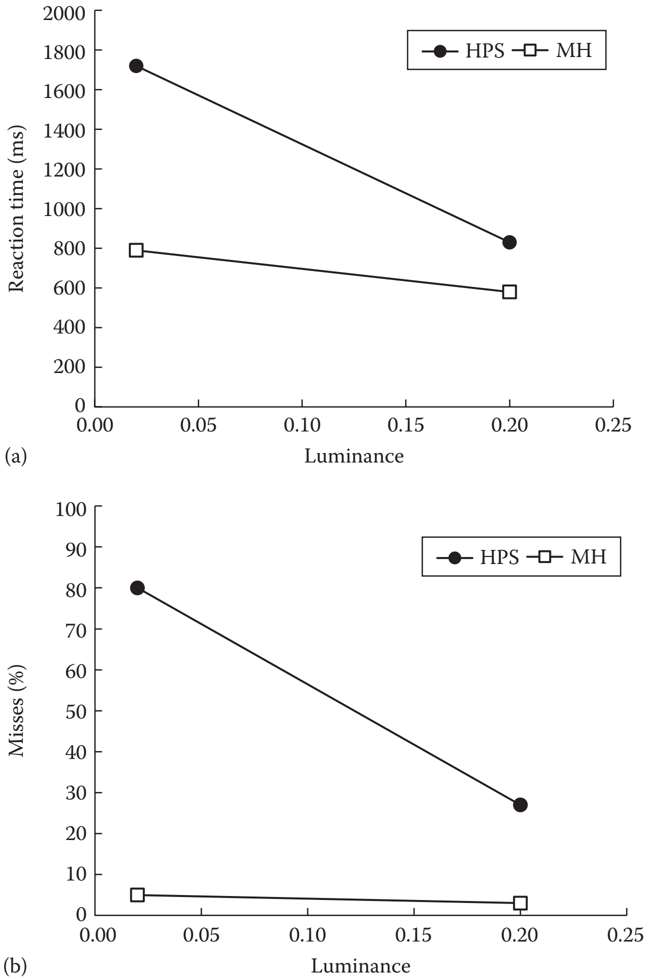


FIGURE 10.26 (a) Mean reaction times (ms) and (b) percentage of misses for changes in a single high-contrast character in a message sign located 15° off-axis for observers looking down a road lit to the same average luminance (cd/m^2) by either HPS or MH lighting. (After Rea, M.S. et al., A field study comparing the effectiveness of metal halide and high pressure sodium illuminants under mesopic conditions, *Proceedings of the CIE Symposium on Visual Scales: Photometric and Colourimetric Aspects*, Teddington, U.K., CIE, Vienna, Austria, 1997.)

measured reaction times to the changes that were detected and the percentage of off-axis signals missed, plotted against the photopic luminance of the road surface. It is evident that the HPS lighting leads to longer reaction times and more missed signals than MH lighting, differences that increase as road surface luminance decreases further into the mesopic. Similar increases in missed off-axis changes under HPS relative to MH illumination have been obtained in other experiments (Bullough and Rea, 2000; Lingard and Rea, 2002). While, the importance of increases in reaction time of the order shown are debatable, there can be little doubt about the importance of missing off-axis changes altogether.

A number of other studies have been made of the effect of light spectrum on visual performance in mesopic conditions (IESNA, 2006). These studies have produced a consistent pattern in which tasks done on-axis, such as measurements of visual acuity (Eloholma et al., 1999a,b) and the visibility distance of small targets (Janoff and Havard, 1997), show no effect of light spectrum at the same photopic luminance in the mesopic range, while tasks requiring off-axis activity, such as measurements of effective field size (Lin et al., 2004) and identifying the direction of movement of an off-axis target while driving (Akashi et al., 2007), do. The effect is that light sources that provide greater stimulation to the rod photoreceptors, that is, with a higher S/P ratio, ensure better off-axis visual performance.

It is now necessary to consider the relevance of this to road lighting practice. Currently, the most widely used light source for road lighting is HPS, but there is rapidly increasing interest in the use of MH and LED light sources. The results discussed earlier have been seized upon by advocates of these light sources as confirming the universal benefits of white light as opposed to orange light, but the implications of the results are rather more complex than such a simple statement suggests. In reality, the benefit of choosing a light source that stimulates the rod photoreceptors more depends on the driver's adaptation luminance, the balance between on-axis and off-axis tasks and the nature of those tasks. Provided the adaptation luminance is such that the visual system is operating in the photopic state, say 3 cd/m^2 and above, there is no effect of light spectrum on off-axis visual performance. If the adaptation luminance is in the high mesopic, say about 1 cd/m^2, the effect of light spectrum is slight. It is only when the adaptation luminance is well below 1 cd/m^2 that the choice of light source is likely to make a significant difference to off-axis visual performance. Mortimer and Jorgeson (1974) found that when driving at night, eye fixations tended to be confined to the lit area, an observation also made by Stahl (2004), at least for straight roads. This suggests that when driving at night on a lit road, the average road surface luminance seen by the driver can be used as a measure of adaptation luminance. If this is so, then the part of the retina receiving light from the part of the road lit by road lighting alone will be operating in the mesopic state, and local and link roads will benefit most from choosing a light source that provides greater stimulation to the rod photoreceptors.

Of course, all these luminances are photopic luminances, calculated using the CIE standard photopic observer. It might be thought that the use of the CIE standard photopic observer for the measurement of light when the visual system is operating in the mesopic state is a fundamental problem. There is no doubt that light sources that more effectively stimulate the rod photoreceptors enhance the performance of off-axis detection tasks when the visual system is operating in the mesopic state, but at what luminance the mesopic state begins is the subject of controversy. A unified model of photopic, mesopic and scotopic photometry based on reaction times has mesopic vision starting at 0.6 cd/m^2 (Rea et al., 2004a), while a model of mesopic effects, based on the performance of tasks claimed to be important to driving, shows mesopic vision having an impact up to 10 cd/m^2 (Elohoma and Halonen, 2006; Goodman et al., 2007). Fortunately, comparisons of the predictions of the two models show only small differences (Rea and Bullough, 2007), which suggests that either of these models, or even the recent CIE mesopic model (CIE, 2010a) which is compromise between them, could be used to evaluate the role of spectral power distribution in road lighting.

Given that road lighting does produce conditions in which the visual system is operating in the mesopic state while driving at night, it is also necessary to consider the nature of the driver's task and the balance between on-axis and off-axis tasks. The nature of the driver's task can vary widely, both in the stimuli presented to the driver and the information that needs to be extracted from them. This is important because the magnitude of any spectral effect on off-axis visual performance will depend on the exact task (IESNA, 2006). For stimuli close to threshold, the spectral effects can be large, but for stimuli well above threshold, the spectral effects may be insignificant. What can be said is that using a light source for road lighting that better stimulates the rod photoreceptors at a given photopic luminance will not make off-axis visual performance worse and may make it better.

As for the balance between on-axis and off-axis tasks, this is important because it is sometimes argued that a light source that stimulates the rod photoreceptors more can be used at a lower road surface luminance than one that provides less stimulation, without penalty. Certainly, the results discussed earlier suggest that, in mesopic conditions, the same off-axis visual performance can be achieved at a lower photopic luminance with an MH light source relative to an HPS light source. However, for an on-axis target, a lower photopic luminance will produce worse visual performance for both light sources. Thus, it is only if off-axis detection is assumed to be the only important task in driving that a reduction in road surface luminance for the MH light source can be justified. There cannot be many drivers who would be willing to deny the importance of both on-axis and off-axis vision for driving. Given that both on- and off-axis vision are important to drivers, a responsible approach to introducing the effect of light spectrum into road lighting practice would be to use light sources with high S/P ratios (see Section 1.6.4.5) without reducing recommended road surface luminances expressed in photopic measures.

10.4.4 Benefits of Road Lighting

Given that the fundamental purpose of road lighting on traffic routes is to enhance the safety of road users by increasing the visibility of the road ahead, it is useful to consider what evidence there is that road lighting achieves this aim (Beyer and Ker, 2009; Rea et al., 2009b). One way to do this is to examine relative accident statistics during the night and day, for lit and unlit roads. Using this approach, Wanvik (2009) concluded that road lighting reduced injury accidents by about 30%. There are two problems with this approach. The first is that it has to be assumed that the changes in traffic densities, levels of intoxication, fatigue and driver demographics from day to night are the same for lit and unlit roads, which may not be true. The second is that it tells us nothing about the effect of different amounts of light on traffic safety. This second limitation can be overcome by collecting accident data from a large number of similar sites with different types and levels of lighting. This was the approach used for a study of the effect of road lighting on traffic safety undertaken in the United Kingdom (Scott, 1980). In this study, photometric measurements were taken of the lighting conditions at up to 89 different sites using a mobile laboratory (Green and Hargroves, 1979). The sites were all at least 1 km long with homogeneous lighting conditions, and both the lighting and the road features had been unchanged for at least 3 years. The sites were all two-way urban roads with a 48 km/h (30 mph) speed limit. The photometric measurements were made with the road dry and the accidents considered were only those that occurred when the roads were dry. Multiple regression analysis was used to determine the importance of various characteristics of the lighting on the night/day accident ratio. The average road surface luminance was found to be the best predictor of the effect of the lighting on the night/day accident ratio. Figure 10.27 shows the night/day accident ratios for the sites plotted against the average road surface luminance. The best-fitting exponential curve through the data is shown, the night/day accident ratios

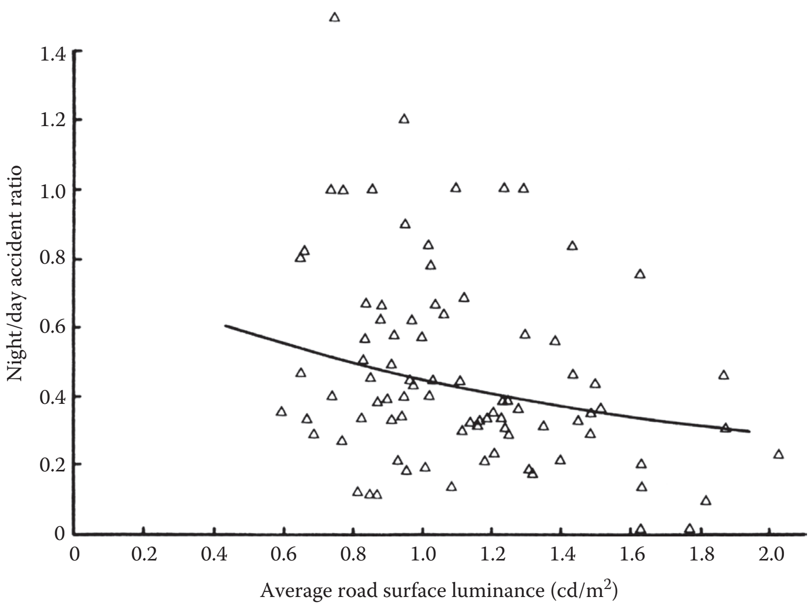


FIGURE 10.27 Night/day accident ratios plotted against average road surface luminance (cd/m^2). The curve is the best-fitting exponential through the data, after weighting each ratio for the number of accidents to which it relates. (After Hargroves, R.A. and Scott, P.P., *Public Lighting*, 44, 213, 1979.)

being weighted to give greater importance to those sites where accidents occurred most frequently. The equation for the curve is

$$N_R = 0.66\ e^{-0.42L}$$

where

N_R is the night/day accident ratio

L is the average road surface luminance (cd/m^2)

It is clear from Figure 10.27 that increasing the average road surface luminance does contribute something to a reduction in accidents at night, but the wide scatter in the individual night/day accident ratios indicates that there are many factors other than the road surface luminance that matter. If we wish to have a clearer picture of the role of lighting in traffic safety, a method that will reduce the amount of noise in the data is required. An elegant solution to this problem is to use the change in lighting associated with the introduction of daylight saving time (DST) (Tanner and Harris, 1956; Ferguson et al., 1995; Whittaker, 1996). In the usual DST system, the clock is moved forward by 1 h in spring and back 1 h in autumn. On both occasions, the effect is to suddenly change a period of driving from light to dark or vice versa. If it is assumed that activity and traffic patterns are governed by clock time, then it is likely that levels of exposure, fatigue, intoxication and driver demographics do not change substantially shortly before and shortly after the DST changeover, so any difference in accidents can plausibly be ascribed to the change in lighting conditions. Sullivan and Flannagan (2002) used data from the years 1987 to 1997 in the Fatality Analysis Reporting System (FARS) database to determine the total number of fatal collisions involving pedestrians in 46 of the 50 states in the United States, for the hour close to the dark limit of civil twilight that showed the greatest change in light level at the DST change (Arizona, Hawaii and Indiana were excluded because they do not have DST, and Alaska was excluded because its solar cycle is markedly different from the other states included).The dark limit of civil twilight is defined as occurring when the centre of the sun is 6° below the horizon. The effect of the DST change on a spring morning is to move the lighting conditions from twilight to night and then back through twilight to day, as day length increases. Figure 10.28a shows the total number of fatal pedestrian accidents occurring at twilight, for the morning transition, in the 9 weeks before and after the spring daylight saving change. It can be seen that in the weeks before the change, there is a steady decrease in the number of fatal accidents, but at the daylight saving change, there is a rapid return to a high level of accidents, a level that then reduces with the increasing day length. Figure 10.28b shows analogous data for the spring evening twilight, for the 9 weeks before and after the daylight saving change. For the evening, the effect of the daylight saving change is to change driving conditions from night to day. The dramatic decrease in the number of fatal pedestrian accidents with this transition is obvious.

This approach has recently been adopted to examine the effect of the change from light to dark on a number of accident types using two databases (Sullivan and Flannagan, 2007). The first is the FARS database (NHTSA, 2006). The second is

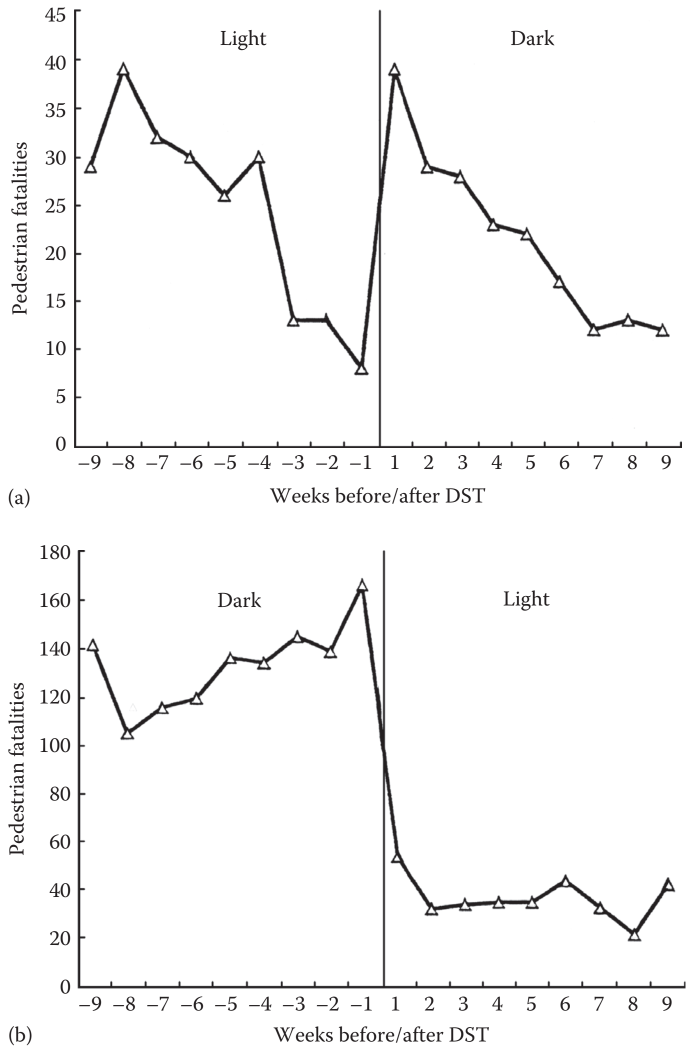


FIGURE 10.28 Cumulative number of pedestrian fatalities in 46 states of the United States, over the years 1987–1997, during twilight, for the 9 weeks before and after the spring DST change (a) for morning and (b) for evening. (After Sullivan, J.M. and Flannagan, M.J., *Accid. Anal. Prev.*, 34, 487, 2002.)

the North Carolina Department of Transportation Crash dataset (NCDOT). For each dataset, accidents that occurred in the 1 h time window that changed from dark to light or from light to dark in the evening when the spring or autumn DST change occurred were totalled over several years. The FARS dataset was used to examine fatal accidents of different types over 18 years (1987–2004). The NCDOT dataset was used to examine different types of fatal, personal injury and property damage-only accidents over 9 years (1991–1999). For both databases, the time window for accidents starts at the dark limit of civil twilight based on standard time and extends forward by 1 h.

TABLE 10.4
Dark/Light Ratios for Fatal Accidents of Different Types for the DST Transition, Based on the FARS Database

Accident Type	Number of Accidents in Dark	Number of Accidents in Light	Dark/Light Ratio
Pedestrians – 18 to 65 years	1635	243	6.73
Pedestrians >65 years	845	126	6.71
Animals	61	11	5.55
Rear-end collision	440	198	2.22
Head-on collision	1058	748	1.41
Collision with parked vehicle	82	58	1.41
Pedestrians <18 years	349	252	1.38
Angle collision	1507	1239	1.22
Miscellaneous	522	460	1.13
Collision with fixed object off road	955	1088	0.88
Overturn	492	691	0.71

Source: Sullivan, J.M. and Flannagan, M.J., *Accid. Anal. Prev*., 39, 638, 2007.

Accidents occurring during the evenings of the 5 weeks on either side of the DST changes were compiled and the ratio of accidents of each type occurring in dark and light conditions calculated. If there is no difference between the number of accidents during dark and light periods, the dark/light ratio will be unity. Dark/light ratios greater than unity indicate that reducing the amount of light available from daylight to whatever is provided by vehicle lighting and road lighting, if present, leads to a greater likelihood of an accident. Table 10.4 shows the dark/light ratios for fatal accidents of different types that are statistically significantly different from unity ($p < 0.05$). The types of fatal accident which had dark/light ratios not statistically significantly different from unity were a side swipe between vehicles moving in the same direction or in opposite directions, a collision with a fixed item and a collision rear to rear. There are three points to be noted from Table 10.4. The first is that some types of fatal accident are strongly influenced by the reduction of visibility that occurs as daylight is replaced with some combination of vehicle lighting and road lighting. Others are not. Adult pedestrians are particularly at risk of fatal injuries after dark, a finding supported by the fact that pedestrian fatalities in Europe increase in winter (ERSO, 2007). Second, some fatal accident types are less likely to occur after dark, specifically, collisions with a fixed object off the road and a vehicle overturning. Such accidents imply a vehicle leaving the road rather than hitting something on the road. Possibly, this is due to the reduction in visibility associated with the onset of darkness, making drivers more circumspect. Third, there is a large difference between the risks of pedestrians under 18 years of age being killed and for adult pedestrians. This probably has more to do with the level of exposure than anything else. Children, particularly younger children, are usually required to be indoors before dark, meaning that their level of exposure is confounded with the change in light level at the DST changeover.

TABLE 10.5
Dark/Light Ratios for Nonfatal Accidents of Different Types for the DST Transition, Based on the NCDOT Database

Accident Type	Number of Accidents in Dark	Number of Accidents in Light	Dark/Light Ratio
Animals	4656	560	8.31
Pedestrians – 18 to 65 years	292	115	2.54
Ran off road – straight ahead	205	96	2.14
Rear-end collision – slow	5466	3708	1.47
Left turn	2265	1819	1.25
Collision with parked vehicle	894	747	1.20
Head-on collision	205	162	1.18
Right turn cross traffic	362	310	1.17
Left turn cross traffic	1340	1167	1.15
Pedestrians <18 years	80	117	0.68
Overturn	52	98	0.53

Source: Sullivan, J.M. and Flannagan, M.J., *Accid. Anal. Prev.*, 39, 638, 2007.

Unlike the FARS database, the NCDOT database is dominated by nonfatal accidents. In the DST sample drawn from the NCDOT database, fatal accidents constituted only 0.5% of the total. Sixty percent of the accidents were property damage only, the rest being accidents involving personal injuries. Table 10.5 shows the dark/light ratios for what are essentially nonfatal accidents that are statistically significantly different from unity ($p < 0.05$). The nonfatal accident types that had dark/light ratios not statistically significantly different from unity were colliding with elderly pedestrians, a rear-end collision when turning, a collision at an angle, a collision while turning right, a side swipe, a collision with an object in the road, a collision with a fixed object, running off the road to right or left and a collision while backing.

There are a number of differences between Tables 10.4 and 10.5. Some of these differences are due to the different accident classification systems used in the two databases, but where the same accident type is considered in both databases, there is some consistency. Adult but not elderly pedestrians are at greater risk of both fatal and nonfatal accidents after dark. Both fatal and nonfatal accidents involving animals are more likely after dark. Both fatal and nonfatal rear-end and head-on collisions are more likely after dark. Both fatal and nonfatal accidents involving collision with a parked vehicle are more likely after dark. Both fatal and nonfatal accidents involving a vehicle overturning are less likely after dark.

Of course, there are also some discrepancies. The dark/light ratio for nonfatal accidents involving pedestrians under the age of 18 years is less than unity, while the dark/light ratio for fatal accidents is greater than unity. This discrepancy is also probably due to the greater vulnerability of children when struck by a vehicle. Another anomaly involves the dark/light ratio for accidents involving animals. The dark/light ratio for nonfatal accidents involving animals is higher than that for fatal accidents. This discrepancy is probably a matter of absolute numbers. The number of accidents associated with animals that prove fatal to humans is small, but the number involving personal injury or property damage is large. Small numbers of accidents make the estimation of dark/light ratios uncertain.

Another interesting feature revealed by a comparison of Tables 10.4 and 10.5 is that for the same accident type, the dark/light ratio for fatal accidents is usually larger than for nonfatal accidents. This may be plausibly explained by the fact that fatal accidents often involve higher speeds than non-fatal accidents. Higher speeds allow less time to respond before collision, a time limit that is shortened further by low visibilities. This suggests that better road or vehicle lighting may be of greater importance for fatal accidents than nonfatal accidents because it offers the possibility of increasing the time available for a response.

The data contained in Tables 10.4 and 10.5 are useful for three reasons. First, they indicate that some types of accident are more sensitive to the reduction in visibility that follows the end of the day than others. If it were possible to identify where the accident types most sensitive to poor visibility were likely to happen, it would be possible to use light as an accident countermeasure more effectively. Second, the data in Tables 10.4 and 10.5 indicate that whatever the standards are for vehicle lighting and road lighting in the United States, they are capable of improvement. Ideally, vehicle and road lighting should reduce the dark/light accident ratio to unity. Third, the dark/light accident ratios can be used to assess the effectiveness of proposed lighting changes. For example, Sullivan and Flannagan (2007) used dark/light ratios for fatal and nonfatal accidents to evaluate the likely effectiveness of several innovative forms of vehicle forward lighting (see Section 10.2.7). For road lighting, the dark/light ratios combined with the frequency and cost of each accident type can be used to provide a monetary value for the benefits of road lighting to set against its undoubted cost.

Nonetheless, the dark/light ratios derived by the DST changeover method are not without limitations. They are derived from the data of one country. Different dark/light ratios are likely to be found in other countries where different driving habits prevail. What constitutes dark will vary from site to site depending on whether road lighting is installed. But the main limit is that they are based on drivers who are travelling around dusk. This may exaggerate the role of animals in accidents because some large animals, such as deer, are crepuscular and so are most active around dusk. It may also show bias because the characteristics of drivers change through the night. Depending on the time of year and the latitude of the country, dusk can range from late afternoon to late evening, clock time. People driving at dusk are much less likely to be intoxicated than those driving late at night (NHTSA, 2006), but they are also more likely to be exposed to higher-density traffic, so in what direction the bias would occur is not at all clear.

While all the previously mentioned limitations are significant, there is one more that is really important. This is simply that the only discrimination made is between day and night. Thus, the dark/light ratios tell us whether or not providing road lighting is likely to be effective in reducing different forms of accidents but not how much is required to reduce the dark/light ratio to unity. Rea et al. (2010b) have developed an approach to this problem. This involves the construction of a photometrically accurate simulation of a road and the use of the relative visual performance (RVP) model (see Section 4.3.5) to estimate the visibility of a target at different positions under different combinations of ambient illuminance and road lighting illuminance as seen by drivers of different ages. In the example given, the road was a simple four-way, right-angle junction. The target was an 18 cm side square with a reflectance of 0.50 mounted vertically 76 cm above road level in front of a car using low-beam headlamps, the positions being systematically arranged along the road as the car approached the junction. The ambient illuminance was 20, 2.0, 0.2 or 0.02 lx corresponding to the illuminances typically found in urban, suburban and rural locations ignoring any road lighting. The road lighting itself varied from no road lighting through localized junction lighting to road lighting extending from the junction along the roads forming the junction. The average illuminance provided on the road by the road lighting varied from low (6 lx on the road and 10 lx at the junction) through medium (9 lx on the road and 15 lx at the junction) to high (18 lx at the road and 30 lx at the junction), all these conditions being seen by drivers of age 30, 45 and 60 years, two seated in two cars stopped at the junction and one approaching the junction. RVP was calculated for all combinations of these variables resulting in a vast amount of data. To simplify matters, the calculated RVP values were placed into four RVP groups: RVP < 0.70 = score 0, 0.70 < RVP < 0.80 = score 1, 0.80 < RVP < 0.90 = score 2 and RVP > 0.90 = score 3. These divisions were chosen because an RVP < 0.70 indicates the visibility is on the escarpment of the RVP surface, 0.70 < RVP < 0.80 is approaching the knee, 0.80 < RVP > 0.90 is on the knee and RVP > 0.90 is clearly on the plateau where there will be very little change in performance for changes in illuminance. Figure 10.29 shows the mean RVP scores achieved for no road lighting and extended road lighting providing low,

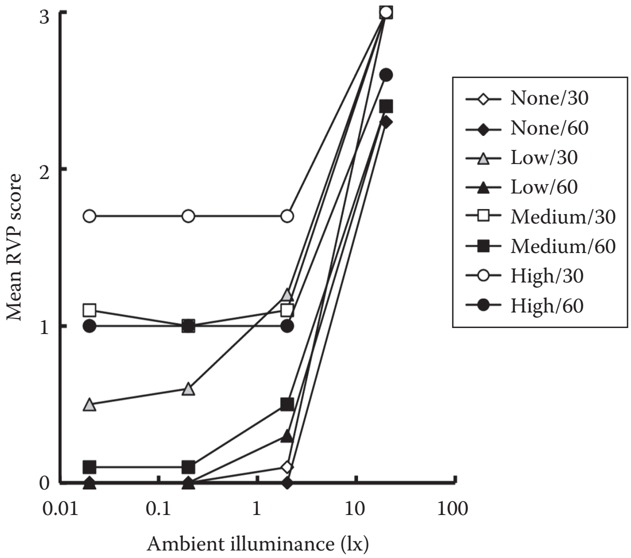


FIGURE 10.29 Mean RVP scores achieved by no road lighting and low-, medium- and high-illuminance extended road lighting, for different levels of ambient lighting and for drivers of 30 and 60 years of age stopped at a junction and looking at an approaching car using headlamps. RVP is calculated for detection of an 18 cm side square target of 0.50 reflectance mounted vertically immediately in front of the approaching car. (After, M.S. et al., *Lighting Res. Technol.*, 42, 215, 2010b.)

medium and high illuminances plotted against different levels of ambient lighting, for drivers of 30 and 60 years of age, for a driver stopped at the junction and viewing the approaching target, where the road is classed as high speed, that is, traffic speeds are likely to be greater than 64 km/h (40 mph). There are three obvious conclusions to be drawn from Figure 10.29: first, when the ambient illuminance is 20 lx, providing road lighting does little to improve RVP score; second, when the ambient illuminance is 2 lx or less, providing road lighting improves the mean RVP score (the greater the illuminance provided by the road lighting, the higher the mean RVP score); and third, older drivers benefit more than younger drivers from road lighting, at least as measured by RVP score.

This is an interesting approach, the mass of data offering many possibilities for analysis. However, before getting too committed to number crunching, it has to be admitted that the approach is theoretical and needs to be validated in some way before its implications can be accepted. One question that needs to be addressed is why the visibility of a small vertical target placed in front of a vehicle should be relevant to the impact of road lighting on traffic safety. It cannot be a matter of detection because the vehicles on the road at night have low-beam headlamps operating, so the vehicles should always be easy to detect. The answer given by Rea et al. (2010b) is that what road lighting delivers is the ability to discriminate the vehicle against its immediate background, details that are valuable for determining the vehicle's position, speed and direction of movement. It is these details that are represented by the small vertical target whose visibility is being calculated. It is the significance of these details for road safety that needs to be established, particularly as they suggest that foveal vision as well as off-axis detection is important for road safety. One attempt to do this relates to the value of localized junction lighting in Minnesota (Rea, 2012). In this study, the improvement of RVP produced by the installation of localized junction lighting was found to reduce car-to-car crashes by 10%. Further data of this type are required.

While the perception of the details of any approaching vehicles may be beneficial for road safety, road lighting also helps the driver control his own vehicle. This is because it provides more information available from optic flow. When driving along a road, the retina receives a moving pattern called the optic flow in which different parts of the visual field appear to flow around the observer at different speeds in varying directions. Analysis of optic flow exposes both the structure of the world around you and your direction and speed of movement through that world (Gibson, 1950). However, absolute speed cannot be obtained from optic flow alone because to judge speed, you need to be able to estimate distance and distance cannot be obtained from optic flow. There are many other visual cues to distance in the retinal image such as perspective, relative sizes of familiar objects, texture gradients, shading and masking of one object by another. Much of this information is only available when the scene is illuminated. Driving at night on headlamps alone limits the amount of distance information available and hence makes it difficult to judge absolute speed visually.

While absolute speed is of interest when driving on an empty road, when there are other vehicles on the road, relative speed is of interest. For example, if you are following another vehicle, then as long as the retinal image size is constant, you are both travelling at the same speed and you are neither increasing nor decreasing your separation. If the retinal image starts to expand, you are closing on the vehicle ahead, and the rate at which you are closing is related to the rate of expansion of the retinal image of the vehicle ahead. How much this change in relative speed matters will depend on the distance between you and the vehicle ahead. This is an easy judgment to make when you are close behind a vehicle, even at night because then your headlamps will illuminate the back of the vehicle ahead, thereby providing a convenient estimate of distance.

The judgment of relative speed is much more difficult when an opposing vehicle is approaching from a distance on an unlit road. Then, headlamps can be seen as two points of light, the separation between them increasing as the vehicle nears. The problem for perception is that unless you also have an estimate of distance, you cannot estimate the implication for speed of a given rate of expansion of headlamp separation. In the absence of road lighting, your estimate of distance may have to rest on an assumed separation of the headlamps on common vehicles or on what the headlamps of the approaching vehicle illuminate. The situation gets even more difficult for a motorcycle when there is only one headlamp. Then, if you want to estimate the approach speed, you have to detect the increase in size of the single headlamp as well as judge the distance. Road lighting makes other cues to approach speed accessible.

In addition to providing information that makes the judgment of position, speed and direction of movement easier for both your own and approaching vehicles, road lighting provides other visual benefits to the driver. They are an increase in the amount of time the driver has before a response is essential, a reduction in the amount of discomfort and disability glare produced by opposing vehicles' headlamps and guidance on the direction of the road far ahead. Anyone who has made the transition from an unlit to a lit section of road while driving using low-beam headlamps will be aware of the immediate sense of relaxation that results. The reason for this relaxation is the greater distances over which objects on and near the road can be detected and hence the longer times available for selecting an appropriate response. This benefit of road lighting will be most evident on high-speed traffic routes where the amount of additional information revealed by the road lighting is likely to be modest, but without road lighting, the required response times are short. Where the amount of additional information revealed by the road lighting is large, as may be the case in urban areas, the sense of relaxation may be less because of the additional information that has to be dealt with. This is particularly so for older drivers whose ability to process visual information rapidly is limited (Owsley and McGwin Jr, 2010).

Road lighting itself will produce some disability and discomfort glare, but given that the standards discussed in Section 10.4.2 are met, the amount of glare produced by road lighting will be much less than that produced by the headlamps of approaching vehicles. For discomfort glare from headlamps, road lighting will tend to increase the adaptation luminance with the result that discomfort glare is reduced. For disability glare from headlamps, road lighting will not change the equivalent veiling luminance, but the impact of the equivalent veiling luminance on luminance contrast will be diminished as the luminance of the background, which is usually the road surface, is increased. Thus, road lighting will always tend to diminish both disability and discomfort glare from headlamps, an achievement that makes driving more comfortable.

As for guidance, the view of road lighting luminaires stretching away into the distance provides easily understandable clues to the run of the road far ahead, further than is possible with retroreflective road markings. Such guidance is most obvious when the road lighting is in a central twin or single-sided layout. Double, staggered or mixed luminaire layouts can be more difficult to interpret.

Clearly, road lighting has a role to play in stabilizing perception and reducing discomfort when driving at night. But it is still not clear how important this is for traffic safety. The results of the DST transition studies shown in Tables 10.4 and 10.5 suggest that the biggest safety benefit of road lighting come from accidents involving people and objects that do not carry their own lighting, such as pedestrians and animals, and hence that will be difficult to detect. The dark/light ratios for accidents involving other vehicles that have headlamps and signal lights, and so should be easy to detect, are much less, although still positive. The traffic safety case for road lighting where pedestrians and vehicles meet is clear. The case where only vehicles interact is less so.

10.4.5 Interaction between Vehicle and Road Lighting

Vehicle lighting is always present after dark and is designed to provide visibility in the absence of road lighting. Road lighting is designed to promote visibility without reference to vehicle lighting. Both vehicle forward lighting and road lighting are designed to make what is ahead visible to the driver. For objects ahead to be visible, they have to have a visual size and a luminance contrast or a colour difference above threshold. Lighting can do little to change visual size and colour difference is only of importance when luminance contrast is low, so the most fitting way to examine the effect of adding road lighting to existing vehicle forward lighting is to estimate the consequences for luminance contrast. The first step in this process is to look at the illuminances received by a target from both vehicle forward lighting and road lighting at different distances from the vehicle. Figure 10.30 shows the illuminances on a square target of side 20 cm with a reflectance of 0.2, placed vertically on the road at different distances from the vehicle and oriented so that the normal to the plane of the target is along the axis of the road (Bacelar, 2004). The vehicle forward lighting used was halogen headlamps conforming to the ECE recommendations. The road lighting consisted of a single-sided layout of five luminaires at 30 m spacing. Each luminaire contained a 150 W HPS light source and was mounted 8 m above the road surface which was representative of a common type of road surface. The resulting photometric characteristics of the road lighting were average road surface luminance = 2.45 cd/m^2, overall luminance uniformity ratio = 0.6 and longitudinal luminance uniformity ratio = 0.7.

From Figure 10.30, it can be seen that the distances from the vehicle can be divided into three zones. Up to 40 m from the vehicle, the illuminance on the vertical target is largely due to the vehicle forward lighting. Between 40 and 60 m, the road lighting and vehicle forward lighting make similar contributions to the vertical illuminance. Beyond 60 m from the vehicle, road lighting makes the major contribution to the illumination of the vertical target, particularly when low-beam headlamps are used. Of course, these boundaries are somewhat moveable, depending on the

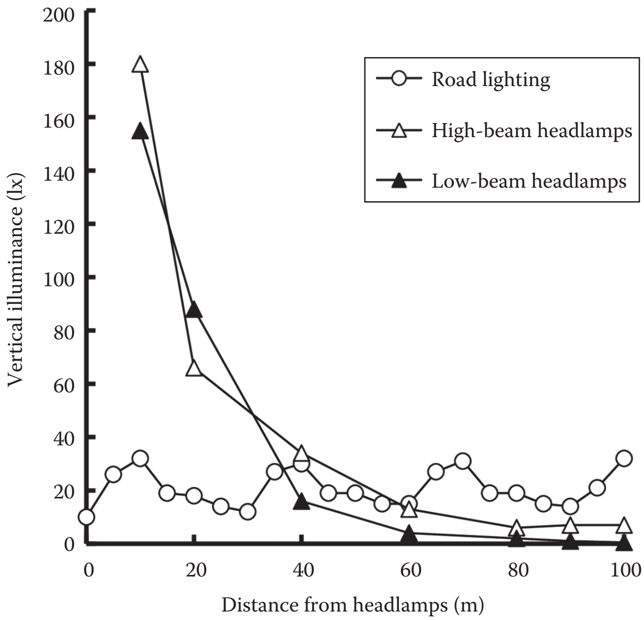


FIGURE 10.30 Vertical illuminance (lx) at road level plotted against the distance from the headlamps (m) for road lighting alone, low-beam headlamps alone and high-beam headlamps alone. The spacing between the road lighting columns was 30 m. (After Bacelar, A., *Lighting Res. Technol.*, 36, 69, 2004.)

forms of the vehicle forward lighting and the road lighting. The road lighting used by Bacelar (2004) produces a higher average road surface luminance than is normally recommended (see Section 10.4.2). For road lighting producing lower average road surface luminances but with the same light distribution, it can be assumed that the boundaries of the three zones will be shifted further away from the vehicle. The same is true for vehicles equipped with HID headlamps. Nonetheless, there will still be three zones, one where vehicle forward lighting is dominant, one where road lighting is dominant and one where the two forms of lighting are approximately equal.

For the distant zone, where very little light from the vehicle forward lighting reaches the target, the presence of road lighting will usually increase the target's visibility. Visibility is measured as visibility level, this being the ratio of the actual luminance contrast of the target to the threshold luminance contrast of the target. Increasing the adaptation luminance by increasing the road surface luminance using road lighting will tend to reduce the threshold luminance contrast, thereby increasing the visibility levels of all targets. While this is generally true, there are some targets for which the visibility level will be reduced. This is because the actual luminance contrast of the target may be reduced by the use of road lighting. One factor that determines whether or not this happens is the relative reflection characteristics of the target and the road surface. Targets that are seen in negative luminance contrast against the road surface, that is, darker than the road surface, will show an increased luminance contrast when road lighting is introduced unless the luminance of the target is increased proportionally more than the road. Targets that are seen in positive luminance contrast, that is, brighter than the road, may show a decreased luminance contrast when the road surface luminance is increased, unless the luminance of the target is increased proportionally. Another important factor is the luminance uniformity of the road lighting. Guler and Onaygil (2003) have shown that road lighting with overall and longitudinal luminance uniform ratios below the minima recommended tends to have larger areas where visibility levels are close to zero.

What this means is that, for the distant zone, introducing road lighting meeting the recommendations will generally increase visibility but may reduce it for specific targets. Within this zone, the range over which targets will remain visible will depend on their visual size. Threshold luminance contrast increases with decreasing visual size (see Figure 2.15), so the visibility level of a target will decrease as the distance between the observer and the target increases until the threshold luminance contrast approaches the actual luminance contrast and the target becomes difficult to detect.

For the near zone, the illuminance on the target is dominated by the vehicle forward lighting, as is the road surface luminance. The increase in adaptation luminance produced by introducing road lighting will again reduce threshold luminance contrasts, although because of the dominance of the vehicle forward lighting, this effect will be small. As for the actual luminance contrast, the impact of introducing road lighting will depend on the relative increases in luminance produced for the target and the road surface. Given that road lighting is designed primarily to light the road surface, it is likely that the increase in road surface luminance will be greater than the luminance of the target. This implies that for targets seen in positive luminance contrast against the road surface when lit by vehicle forward lighting alone, the actual luminance contrast will be reduced. Whether this reduction leads to a decreased visibility level will depend on the extent to which the decrease in actual luminance contrast is compensated by the reduction in threshold luminance contrast. For targets seen in negative luminance contrast against the road surface when lit by vehicle forward lighting alone, the introduction of road lighting will most likely lead to an increase in actual luminance contrast which, together with the reduction in threshold luminance contrast, will always produce an increase in visibility level.

It is in the intermediate zone that things get really interesting. In this zone, both road lighting and vehicle forward lighting make similar contributions, although the road lighting emphasizes the horizontal road surface, while vehicle forward lighting emphasizes the vertical target. Bacelar (2004) has calculated the visibility level from measurements of target and background luminance for the conditions described earlier and using the model of target visibility developed by Adrian (1989). The target was placed at a constant distance of 40 m from the vehicle for low-beam headlamps and 90 m for high-beam headlamps. The stopping distance is assumed to be 40 m for inner-city areas where vehicle speeds are of the order of 50 km/h (31 mph), and 90 m is the stopping distance for suburban areas where vehicle speeds are in the range 75–110 km/h (47–68 mph). The target was moved in 5 m steps along the road between the second and third road lighting columns, successive columns being separated by 30 m. Figure 10.31 shows the variation in visibility level for headlamps alone, road lighting alone and headlamps and road lighting together. For headlamps alone, the visibility levels are constant because the target is at a constant distance from

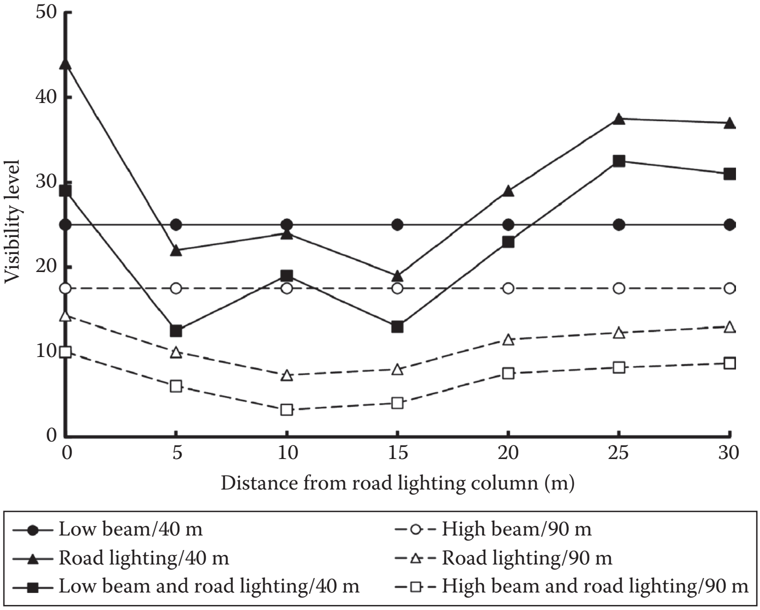


FIGURE 10.31 Visibility levels calculated from luminance measurements taken for a vertical target of reflectance 0.2 at a distance from the driver of 40 m for low-beam headlamps and 90 m for high-beam headlamps, plotted against the position of the target relative to a road lighting column (m). Successive road lighting columns were separated by 30 m. Measurements were made for headlamps alone, road lighting alone and headlamps and road lighting together. (After Bacelar, A., *Lighting Res. Technol.*, 36, 69, 2004.)

the vehicle. Visibility levels are lower at 90 m using high-beam headlamps alone than at 40 m using low-beam headlamps alone because of the lower illuminance on and smaller angular size of the target at the greater distance. A lower illuminance implies a lower adaptation luminance and consequently a higher threshold luminance contrast, as does the smaller angular size of the target.

For road lighting alone, there is some variation in visibility level because of the variations in illuminances on the road and target at different positions relative to the road lighting luminaires. The visibility levels are lower at 90 m than at 40 m because of the smaller visual size of the target. When the target is between 5 and 20 m from the column and 40 m from the vehicle, low-beam headlamps and road lighting together produce lower visibility levels than either system alone. When the target is 90 m from the vehicle and high-beam headlamps are used, high-beam headlamps and road lighting together produce lower visibility levels than either system alone, at all positions. A similar pattern of visibility levels for different combinations of vehicle forward lighting and road lighting has been found by others (Guler et al., 2005). The visibility level believed to be required for a high level of correct detection that is visually easy is about 20–25 (Blackwell and Blackwell, 1977; Brusque et al., 1999).

So far, this discussion of visibility has concentrated on the effect of introducing road lighting on adaptation luminances and target luminance contrasts. But road lighting may also cause disability glare. Fortunately, Bacelar (2004) also calculated

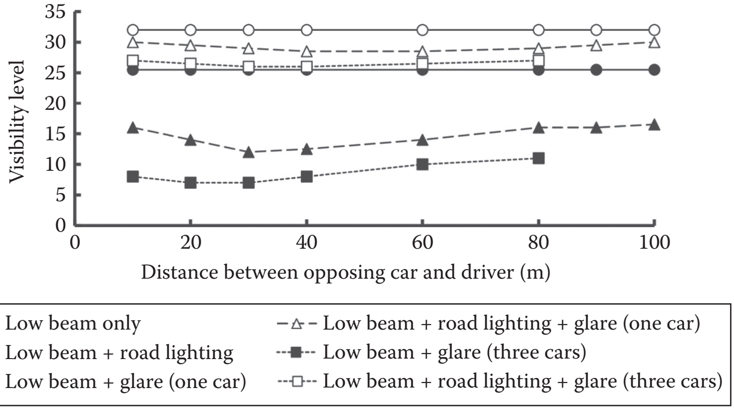


FIGURE 10.32 Visibility levels calculated from luminance measurements taken for a vertical target of reflectance 0.2 at a fixed position relative to the road lighting and 40 m from the driver of a vehicle using low-beam headlamps, with and without road lighting and with none, one or three opposing vehicles, plotted against the distance (m) between the opposing vehicles and the driver. (After Bacelar, A., *Lighting Res. Technol.*, 36, 69, 2004.)

the visibility level of the target in a fixed position relative to the road lighting and 40 m ahead of the vehicle, which was using low-beam headlamps. Figure 10.32 shows that, for this position, introducing road lighting results in an increase in the visibility level from 25 to 33, suggesting that, with respect to visibility, the changes in road surface luminance and the actual luminance contrast of the target caused by adding road lighting are more than enough to offset any additional scattered light in the eye.

Of course, this may not always be true. Another interaction of road lighting and vehicle lighting involves the change in the effects of the disability glare caused by the headlamps of opposing vehicles. Bacelar (2004) also reports changes in visibility level for the target positioned at a fixed point 40 m ahead of a vehicle using low-beam headlamps, with and without road lighting, in the presence of one or three opposing vehicles also using low-beam headlamps. Figure 10.32 shows the calculated visibility levels, for different distances between the vehicles, with and without the road lighting. It is clear that disability glare from opposing vehicles reduces visibility levels, that three opposing vehicles produce greater reductions in visibility levels than one opposing vehicle and that the reduction in visibility level caused by disability glare from opposing vehicles is less when road lighting is present.

These results suggest three conclusions. The first is that introducing road lighting is likely to improve the visibility of most targets, particularly when they are in the distant zone. The second is that there can be no guarantees that visibility will improve for all targets. There are some targets for which the combination of light distributions from the vehicle forward lighting and road lighting and the reflection properties of the target and the road surface may lead to reduced visibility. The third is that introducing road lighting alleviates the effects of disability glare from opposing vehicles on visibility.

10.5 MARKINGS, SIGNS AND TRAFFIC SIGNALS

Today, drivers are faced with a plethora of markings, signs and signals designed to inform and regulate their behaviour, some fixed, some changeable, some unlit, some lit, but all needing to be seen by day and night. The form and location of markings, signs and signals are strictly controlled so as to ensure consistency across road networks, although different countries have different rules (FHWA, 2003; DfT, 2005). The factors considered in designing markings, signs and signals are the distances from which they need to be visible: their shapes and colours, shape and colour being used as cues to meaning as well as being important for visibility; the advantages and disadvantages of pictograms rather than text; and the need for some means to attract attention to the sign or signal.

10.5.1 Fixed Road Markings

The main role of fixed road markings is to provide visual guidance and lane definition for drivers, although markings are used for many other purposes such as indicating parking places and speed limits. Drivers need both long-range guidance (more than 5 s preview time) and short-range guidance (less than 3 s preview time) (Rumar and Marsh II, 1998). Long-range guidance is accessed intermittently and consciously, using foveal vision. Short-range guidance is accessed continuously and unconsciously, using peripheral vision. Road markings can provide both short- and long-range guidance.

Road markings usually consist of a paint or thermoplastic material containing spherical retroreflective beads (see Section 10.3.6). The paint or thermoplastic material is a high-reflectance, diffuse reflector, which ensures the mark will be seen in positive luminance contrast against the low-reflectance road surface during daylight. At night, the luminance of the white paint has two components, the diffuse reflected component mainly provided by any road lighting and the retroreflected component from the vehicle headlamps (CIE, 1999). Where there is no road lighting, the luminance depends almost entirely on the retroreflective materials. The greatly enhanced reflection of these materials in the direction of the vehicle means that the luminance of the markings will be much greater than the luminance of the adjacent road surface, the resulting luminance contrast making the markings visible at a distance. The main limitation of such markings is that they tend to lose their retroreflective properties with wear and they tend to disappear when the road is covered with water, the water surface forming a specular reflector above the markings which reflects the grazing-incident light from the vehicle's headlamps along the road away from the driver before it reaches the retroreflectors. As a result, visual guidance is much reduced at the time when it is most required (Rumar and Marsh II, 1998).

A different device used to enhance lane definition and guidance in rain and fog is the individual retroreflector, originally known as a cat's-eye but now commonly called a road stud. All road studs place the retroreflectors high enough above the road surface to stand above the usual water levels occurring on a road, although this can make them prone to damage by snow ploughs. Road studs can be fitted with filters so that colour can be used to carry a message. For example, road studs acting as lane dividers are usually white, while those acting as road edge markers are conventionally red on the nearside and orange of the offside of the road. Where the edge of a road can be crossed, as at a slip road off a major road, the colour of the road studs changes from red to green.

Road studs depend for their visibility on light from a vehicle's headlamps. This inevitably limits the distance over which guidance is delivered to less than 100 m. An alternative now available is the photoelectric-powered road stud containing an LED. Such a stud is self-luminous. By installing studs of this type at regular intervals along a road, visual guidance is available over much longer distances, typically up to 1000 m, and around curves in the road. Anecdotal reports claim that such installations have had dramatic effects on the number of accidents occurring on unlit roads subject to mist and fog.

The effects of road marking on drivers' behaviour are mixed. Adding lines marking the edges of a road where previously there had been no marking results in increased driving speeds with the lateral position of the vehicle being closer to the edge of the road (Rumar and Marsh II, 1998; Davidse et al., 2004). When edge lines are added to an existing centreline, there is no overall change in speed, but when a centreline marking is replaced with edge lines, there tends to be a decrease in speed (Davidse et al., 2004). The rationale for such changes in behaviour lies in the driver's confidence about the width of the road and what lies ahead. Providing edge markings, or a centreline, on a previously unmarked road will increase the amount of visual guidance and confidence in where the road goes, hence the increase in speed. Adding edge markings to a road with a central line marking adds little to visual guidance, so a change in speed is unlikely. Removing central marking and replacing it with edge markings may have the effect of making the road appear narrower, hence the reduction in speed. These examples serve to make a basic point that providing better visual guidance to the driver at night may not result in safer driving. There are two opposing views on the value of road marking. One view holds that better visual guidance leads to smoother and safer driving. The other is that better visual guidance leads to overconfidence in where to go without consideration of how to get there. The problem this conflict exposes is that while some visual guidance is certainly necessary and road markings are a convenient way to provide it, markings only address one part of the driver's task. An overemphasis on visual guidance and a neglect of the other aspects of the driver's task may diminish traffic safety rather than improve it.

10.5.2 Fixed Signs

Another common feature of roads is fixed signs mounted beside or over the road giving information on directions, lane changes, speed limits, etc. The size, shape, colour and content of such signs have been extensively studied (Forbes, 1972; Mace et al., 1986). The first question of interest here is whether or not such signs should be illuminated and, if so, how? The decision on whether or not to illuminate a sign depends first and foremost on the distance at which the sign needs to be detected and the distance at which it needs to be legible. These distances depend on the speed and density of traffic approaching the sign and whether the driver has to carry out some manoeuvre in response to the sign. High speeds, dense traffic and the need for a manoeuvre all increase the distances at which the sign needs to be detected and legible. Other factors to be considered are the complexity and brightness of the background against which the sign has to be seen, the location of the sign relative to the driver and the size of the sign. The more complex the background, the brighter the ambient light level, the further the sign is from the edge of or above the road and the larger the sign, the more likely it is that individual lighting should be provided. Individual sign lighting is necessary because the alternative sources of light, road lighting and headlamps, are inadequate. IESNA (2001) recommends a maintained average illuminance on the sign of 140 lx for rural areas, 280 lx for suburban areas and 560 lx for urban areas. The maximum illuminance uniformity ratio (maximum/minimum) associated with these recommended maintained illuminances is 6:1.

An alternative approach to external lighting of signs is the internally illuminated sign. Such signs consist of an inter-reflecting box containing a light source, with the front face of the box providing the information. Both the reflection and transmission properties of the front face are important because the sign has to be legible by both day and night and should look the same under both conditions. It is the reflection properties that dominate the appearance of the sign by day and its transmission properties that dominate by night. The great advantage of the internally illuminated sign is that, compared with external sign lighting, it produces much less light pollution. The risk with internally illuminated signs is that, at night, the luminance is so high that the sign itself becomes a glare source. IESNA (2001) recommends maintained average luminances for white translucent material (reflectance = 0.45), at night, these being 20 cd/m^2 for rural areas, 40 cd/m^2 for suburban areas and 80 cd/m^2 for urban areas. The luminance uniformity ratio (maximum/minimum) should not exceed 6:1.

Where neither external nor internal sign lighting is provided, the luminance of the sign at night is dependent on the illumination provided by the headlamps of approaching vehicles, the effectiveness of the retroreflective treatment of the material from which the sign is constructed and the angular separation of the driver from the headlamps (Sivak and Olson, 1985). Olson et al. (1989) examined how the detection distances for differently coloured retroreflective sign materials varied with the effectiveness of the retroreflective material expressed as the specific intensity/unit area of material. Specific intensity is the luminous intensity emitted by the retroreflector per unit of illuminance received at the retroreflector. The distances were obtained from observers driving along unlit roads at night using headlamps alone. There were two linear relationships between the logarithm of the specific intensity/unit area and detection distance, one for yellow, white, blue and green materials and one for red and orange materials. For all colours, the higher is the specific intensity/unit area for the material, the greater is the detection distance (Figure 10.33).

As for the angular separation of the driver from the headlamps, this matters because the retroreflective materials used in signs reflect the incident light back along its own path, that is, light received at a sign from a headlamp will be reflected back to the headlamp. Of course such material is not perfect so there will always be some spread in the reflected light distribution. The position of the driver relative to the headlamps is not usually a problem for cars, but for large trucks, it can be. Sivak et al. (1993) have shown that the luminance of retroreflective signs can be much less

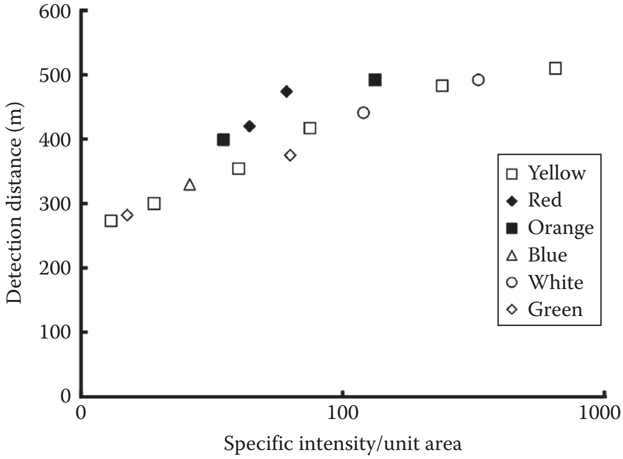


FIGURE 10.33 Mean detection distances (m) for road sign materials of various colours plotted against the efficiency of the retroreflective material, measured as the specific intensity/unit area of the material (cd/lx/m^2). (After Olson, P.L. et al., *The Detection Distance of Highway Signs as a Function of Color and Photometric Properties*, Report UMTRI-89-36, University of Michigan Transportation Research Institute, Ann Arbor, MI, 1989.)

for truck drivers than for car drivers and that such reduced sign luminances will seriously reduce the detection distances of signs.

Another area of concern for signs, both lit and unlit, is the background against which the sign is seen. The background can be important for two different reasons. The first is the presence of a very bright light source close to the sign. Such a source can produce enough disability glare to make the sign invisible. The classic example of this is a sign with the setting sun immediately adjacent to it. This problem is usually solved by surrounding the sign with a low-reflectance screen that cuts off the view of the sun within a few degrees of the sign. The second is where the background against which the sign is seen is visually complex so that the sign is just one sign among many. This often occurs in city centres where there are a multitude of advertising signs of high luminance to compete with the road sign. Schwab and Mace (1987) examined the detection and legibility distances for signs seen against backgrounds of different complexities. They found that the more complex was the background, the shorter was the detection distance, but there was little effect on legibility distance. This is not surprising because legibility is primarily dependent on the details within the sign when the sign is fixated while a sign is usually first detected off-axis. The effectiveness of off-axis detection during visual search will be influenced by the presence of competing visual information.

10.5.3 Changeable Message Signs

Another sign that is found with increasing frequency is the changeable message sign (CIE, 1994b). These signs are used to provide information about temporary road conditions, such as the presence of road works, variable speed limits and traffic congestion. Changeable message signs usually use a series of luminous pixels to

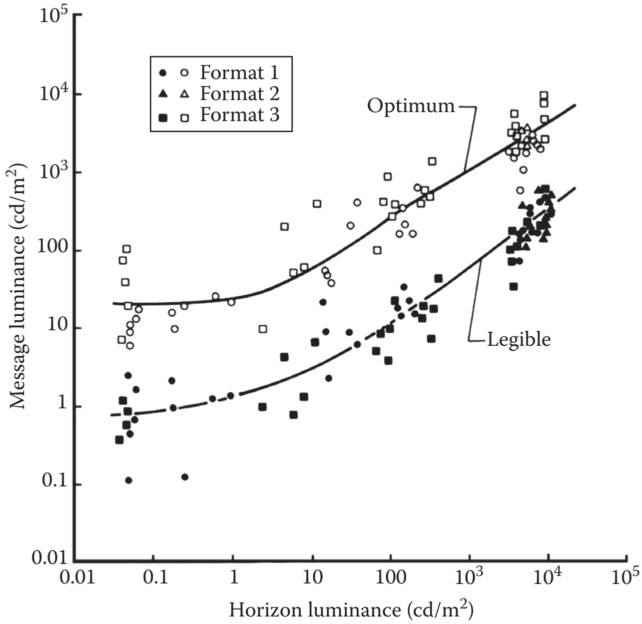


FIGURE 10.34 Message luminances (cd/m^2) set by individual subjects for the number 5 presented in three different formats on a self-luminous message sign, seen from 100 m, plotted against horizon luminance (cd/m^2). The luminances were set to match two different visibility criteria at different times of day and night and hence for different horizon luminances. The criterion optimum is based on the perception that the display is conspicuous but not glaring. The criterion legible is based on the perception that the display is just recognizable. The three formats used different numbers of pixels to form the number 5. Specifically, format 1 = 23 pixels, format 2 = 50 pixels, format 3 = 141 pixels. (After Padmos, P. et al., *Lighting Res. Technol.*, 20, 55, 1988.)

display a text message or pictogram. Padmos et al. (1988) carried out field evaluations of self-luminous message signs mounted above the road so that the immediate background was the sky. Figure 10.34 shows the mean message luminances set for three different formats of the number 5, for two different visibility criteria, plotted against the horizon luminance. The number 5 was viewed from 100 m. The message luminance is given by the equation

$$L_{mes} = 10^6 \lozenge \frac{I_{px}}{d^2}$$

where

L_{mes} is the message luminance (cd/m^2)
I_{px} is the pixel luminous intensity (cd)
d is the distance between pixels (mm)

Figure 10.34 shows that the visibility of the message varies with the horizon luminance; the higher the horizon luminance, the higher the message luminance required for the message to be visible. By using other visibility criteria, Padmos et al. (1988) were able to show that the message luminances necessary for a rating of *optimum* on a bright day would be rated as *glaring* at night. This finding implies that some degree of luminance control is necessary to ensure comfortable and effective viewing of the message by day and night. Padmos et al. (1988) suggest that a sufficiently legible but not too bright message can be obtained by a two-step message luminance, 4000 cd/m^2 by day and 100 cd/m^2 by night, although three steps (4000, 400 and 40 cd/m^2) would be better.

A changeable message sign is only as useful if it gives information that is not otherwise available to the driver, such as an accident causing congestion some miles ahead that can be avoided by taking a different road or a change of speed limit made at times of heavy congestion with the intention of maintaining a smooth and steady traffic flow. Where the message is relevant as regards event, location and timing, changeable message signs can have a beneficial effect on traffic safety. Alm and Nilsson (2000) conducted an experiment looking at the effect of different message content on drivers' behaviour. In a driving simulator, drivers were faced with three incidents, a queue of cars moving at 30 km/h (18 mph), road works requiring a lane change and an accident requiring a lane change. Five levels of information were provided at a distance of 1000 m from the incident (Table 10.6). Figure 10.35 shows the mean speed plotted against distance from the slow-moving traffic queue. It is evident that any warning results in a slower approach to the slow-moving traffic queue than when no warning is given. Indeed, one of the drivers who did not receive a warning failed to slow soon enough and collided with the back of the queue. Figure 10.36 shows the mean speed of approach for the accident. Again, the speed of approach is reduced when any form of warning is given. Interestingly, when the message contains a recommended action, namely, to use the left lane, lane changing occurs earlier, but the speed past the accident is faster than when less information is given. There can be little doubt that messages that are correct in describing event, location and appropriate action are helpful to drivers.

TABLE 10.6
Levels of Information Provided to Drivers in a Study of the Effect of Message Content on Driver Behaviour

Message Level	Information Provided	Example of Message
0	None	—
1	Warning (flashing red light)	Warning
2	Warning, nature of incident	Warning, congestion
3	Warning, nature of incident, distance to incident	Warning, road works, 1 km ahead
4	Warning, nature of incident, distance to incident, recommended action	Warning, accident, 1 km ahead, use left lane

Source: Alm, H. and Nilsson, L., *Transport. Human Fact.*, 2, 77, 2000.

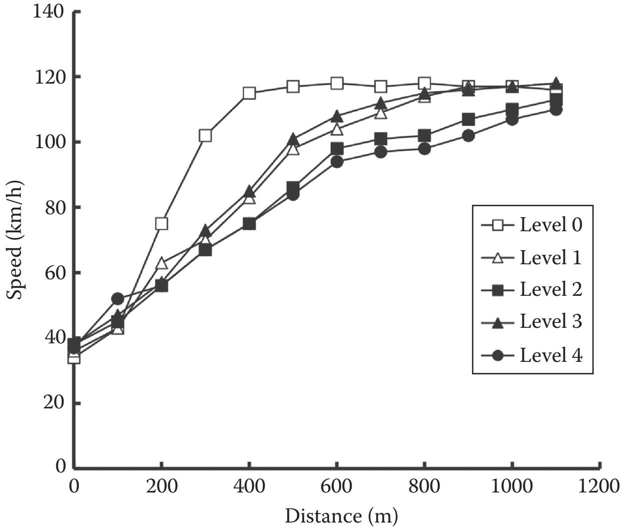


FIGURE 10.35 Mean speed (km/h) plotted against distance (m) from a slow-moving queue of traffic for the five levels of message content listed in Table 10.6. (After Alm, H. and Nilsson, L., *Transport. Human Fact.*, 2, 77, 2000.)

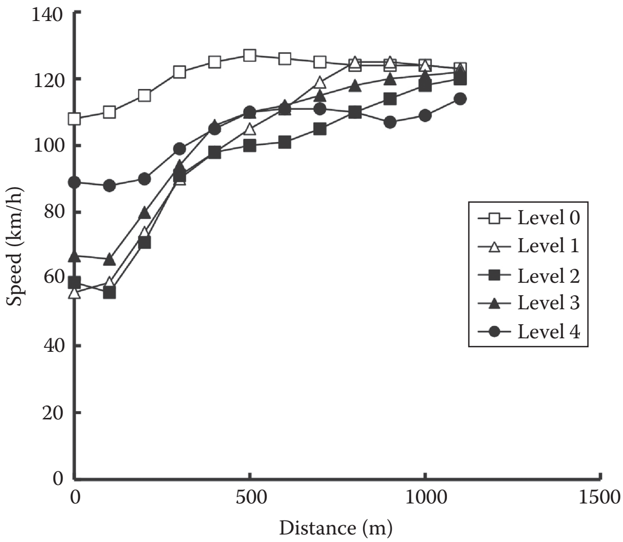


FIGURE 10.36 Mean speed (km/h) plotted against distance (m) from an accident requiring a change of lane for the five levels of message content listed in Table 10.6. (After Alm, H. and Nilsson, L., *Transport. Human Fact.*, 2, 77, 2000.)

10.5.4 Traffic Signals

A ubiquitous feature of roads in urban and suburban areas is the traffic signal using either incandescent or, increasingly, LED light sources. Traffic signals are placed at intersections to identify priorities for both vehicular and pedestrian traffic. The photometric and colorimetric characteristics of traffic signals are closely regulated in terms of their luminous intensity distributions and colour, the latter because the meaning of the signal is given by its colour (ITE, 1985, 2005; CIE, 1994a; European Committee for Standardization, 2006). These recommendations are consensus decisions made by a committee, but those decisions are based, at least in part, on studies of the reaction time to the onset of the signals and the number of signals that are not detected under different conditions. Bullough et al. (2000) have reported an extensive series of measurements of reaction time and missed signals using a tracking task requiring continuous fixation and simulated traffic signals occurring a few degrees from the fixation point, the traffic signals being provided by both incandescent and LED light sources. Reaction times for all three signal colours tended to become shorter as signal luminance increased until a minimum was reached. However, small changes in reaction time are of little significance for traffic signals because of the delays built in to the sequencing of the signals. Much more important are signals that are missed altogether. Figure 10.37

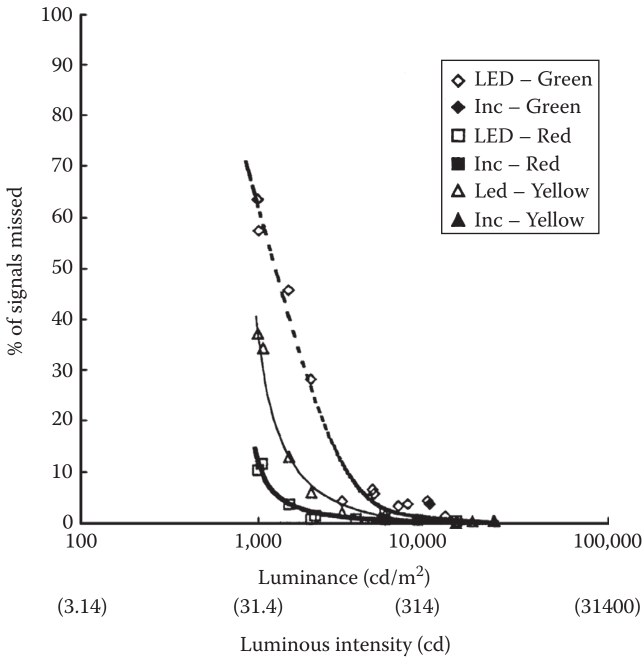


FIGURE 10.37 Percentage of signals missed for each signal colour plotted against signal luminance (cd/m^2). The signals were provided by either LED or filtered incandescent light sources. To be counted as a missed signal, the signal had to have been on for 1 s without a response from the subject. The second horizontal axis is the luminous intensity (cd) corresponding to the signal luminance (cd/m^2) for a 200 mm diameter signal. (After Bullough, J.D. et al., *Transport. Res. Rec.*, 1724, 39, 2000.)

shows the percentage of missed signals for three traffic signal colours, over a range of signal luminances, seen against a 5000 cd/m^2 large area background, that is, against a simulated daytime sky. A missed signal was one that was lit for more than 1 s without a response from the subject. It is evident that increasing the signal luminance reduces the percentage of missed signals until a minimum level is reached. This suggests that the higher is the luminous intensity, the better is the signal, but there is a limit as to how far the luminous intensity of a signal can be taken. A traffic signal has to be seen both day and night. A higher luminous intensity is of value during the day because it will tend to increase the conspicuity of the signal, but by night, a high luminous intensity can become a source of discomfort and even disability glare. Bullough et al. (2001b) measured the percentage of people considering traffic signals of different luminances uncomfortable when viewing them directly (Figure 10.38). Such data can be used to set desirable traffic signal maximum luminances at night, which might be lower than the maximum allowed by day.

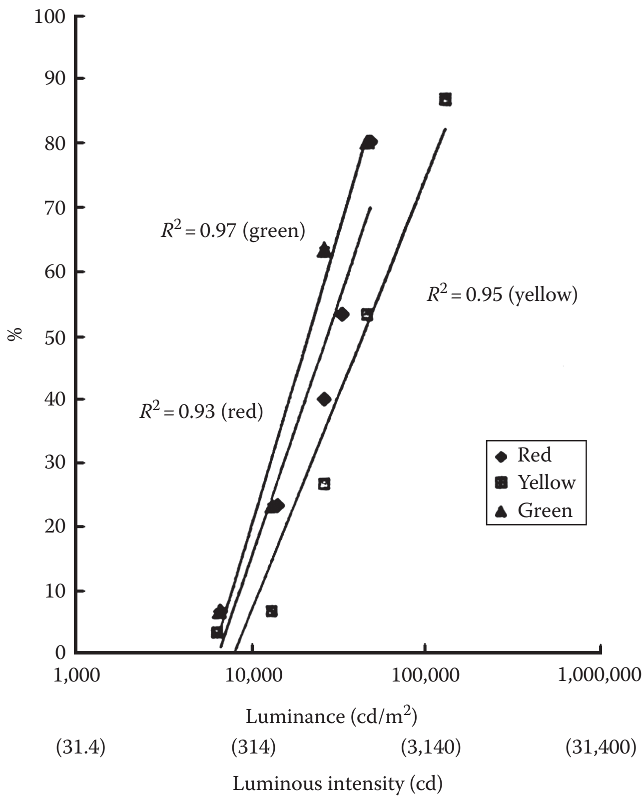


FIGURE 10.38 Percentage of subjects considering a signal uncomfortable for the three signal colours seen in darkness, plotted against signal luminance (cd/m^2). The signal simulates a 200 mm diameter signal seen from a distance of 20 m. The second horizontal axis is the luminous intensity (cd) corresponding to the signal luminance (cd/m^2) for a 200 mm diameter signal. (After Bullough et al., 2001b.)

10.6 SUMMARY

Lighting for driving has several components. The first is vehicle lighting. Vehicle lighting takes two forms: forward lighting, designed to enable the driver to see after dark, and signal lighting, designed to indicate presence or give information about the movement of a vehicle by day and night. Forward lighting is to see by. Signal lighting is to be seen. Both types of vehicle lighting are closely regulated. For signal and marking lights, the regulations are based on the visibility of the lights, which in turn is dependent on the luminous intensity, area and colour of the light. For forward lighting, the regulations reflect a balance between the desire to brightly illuminate whatever is ahead of the vehicle and the need to avoid blinding an approaching driver. The result of this compromise is often to limit the distance at which significant obstacles can be seen to less than that needed for safety. Various methods have been proposed to increase forward visibility without increasing glare, for example, using IR radiation and sensors or adaptive headlamp systems that automatically change according to the prevailing road conditions. Both these systems are starting to appear at the top end of the car market.

The second component involved in lighting for driving is road lighting. The principle behind road lighting is to light the road surface brightly enough so that objects on the road are seen in silhouette against the road. The value of light as an accident countermeasure has been established for fatal accidents involving pedestrians at night, where the low visibility of the pedestrian is a contributory factor to the accident. There are well-recognized recommendations of road surface luminance, luminance uniformity and disability glare for roads with different traffic speeds, traffic densities and levels of pedestrian conflict, but there is no recommendation as regards light spectrum. Recent research has shown that a light spectrum that effectively stimulates the rod photoreceptors of the retina will lead to shorter reaction times and fewer misses for off-axis targets than one that does not stimulate the rod photoreceptors, in mesopic conditions.

A third component in lighting for driving is the visibility of road markings, road signs, and traffic signals. Road markings are used to indicate lane boundaries, bends in the road, areas where overtaking is prohibited, etc. Road markings usually consist of a paint or thermoplastic material containing spherical retroreflective beads. Another form of road marking consists of retroreflective road studs. Retroreflective materials reflect light back in the direction from whence it came, regardless of the angle of incidence, so they are effective when illuminated by vehicle forward lighting alone. Signs giving information on speed limits, directions, etc., either have their own lighting, usually where they need to be seen from a long distance, or are illuminated by light from the vehicle's forward lighting. In the latter case, the signs are usually coated in some form of retroreflective material.

These signs rely on reflected light to be seen. Other types of sign emit light. Probably the most ubiquitous are traffic signals designed to control traffic flow. The luminous characteristics of traffic signals are closely regulated, but in different ways, in different parts of the world. The basis of these characteristics is the reaction time to the onset of the signals and the proportion of missed signals. Another type of sign increasingly used on roads is the changeable message sign. Both traffic signals and changeable message signs have to be designed so that they are bright enough to be conspicuous and legible by day, but not so bright that they become glare sources by night.

Given the number of lighting components involved in helping the driver, it is remarkable that their interaction is largely ignored. This is most marked for road lighting and vehicle forward lighting. Vehicle forward lighting primarily lights the vertical surfaces of objects on the road, while road lighting primarily lights the horizontal road surface. The combined effect can be to eliminate the contrast of an object against the road, yet only rarely is the combined effect of vehicle lighting and road lighting considered. The physics of what is required to make an object on or near the road visible and the methods suitable for delivering information to the driver quickly and simply are well understood. What appears to be missing is the will to consider them as an integrated system.

11 Lighting for Pedestrians

11.1 INTRODUCTION

The lighting of traffic routes is designed primarily for the driver. But drivers are not the only users of the streets at night, people on foot are also likely to be about, and they benefit from some lighting. What form this lighting should take is given in national standards (BSI, 2003), guidance documents (CIE, 2010c) and books (Leslie and Rodgers, 1996; ILE, 2005). Lighting for pedestrian use at night is provided on residential roads and in car parks, where there are likely to be vehicles moving close by, and in pedestrianized areas and public parks, where there are not. This lighting can take various forms from conventional road lighting through area floodlighting to the more exotic forms of landscape lighting (Moyer, 2005). This chapter will review the aspects of lighting that influence the visibility, safety and comfort of pedestrians.

11.2 WHAT PEDESTRIANS WANT FROM LIGHTING

Davoudian and Raynham (2012) had people walk down a number of residential streets in London after dark while wearing an eye-tracking device. They were told simply to cover a set route given to them on a map but had no other specified task. The eye-tracking device records where the pedestrian is looking at any moment. Analysis of the records showed that the pedestrians spent about 40%–50% of the time looking at the pavement ahead but for the rest of the time, their eyes were fixated on objects that attracted attention, such as people approaching, and objects of personal interest as well as vehicles driving nearby and signs giving useful information. What this suggests is that pedestrians want to be able to move safely over the ground, to see where they are, and to appreciate their surroundings

The desire to be able to see where you are is a very basic desire. Anyone who has experienced a dense fog or a snow whiteout will know the feeling of disorientation that goes along with not be able to discriminate anything around you. Lighting aids orientation by revealing the immediate world in detail and the distant world in form. Both are important. For someone seeking a specific house, being able to see the house number is important. For someone seeking a landmark by eye, being able to see its form in the distance is useful.

Moving along a route requires the pedestrian to cover the ground. This may mean walking on uneven surfaces, over slippery surfaces, and around obstacles, such as lamp columns. Failure to navigate over and around these features can lead to injuries. In addition, there is the special case of having to cross the road where there are vehicles approaching. Pedestrian crossings are designed and lit to make this safe.

Being able to see where you are has implications beyond orientation. Seeing your surroundings can give you an idea of the sort of area you are in and hence the risk of assault or harassment. For example, observing that a greengrocer's shop has metal bars on the windows when it is shut will tell you that this is a rough area where the risk of crime is high. More immediately, observing a group of young men loitering on a corner or a pair of drunks coming towards you along the street might give a nervous pedestrian pause for thought. If that pedestrian were to decide that discretion was the better part of valour, then there would be a need to decide on how to escape. Again, this requires being able to see the lie of the land and hence to identify an alternative and safer route.

But everyday experience suggests that the previous example is not all that pedestrians want from lighting. Even when orientation is easy and there is no evident risk of assault or harassment, there is still a desire to avoid visual discomfort. All forms of lighting can cause discomfort through glare. Lighting for pedestrian areas is no exception so care is required to avoid glare particularly where low mounting heights are used.

Finally, it is important to emphasize that the lighting of an area can do much more than simply allow orientation, enhance safety and eliminate discomfort. There is a positive side to lighting. One aspect of lighting that can be positive is the colour rendering property of the light source used. Unfortunately, many of the light sources used for the lighting of pedestrians are inappropriate for the environment and the people in it. Some used for road lighting, such as low-pressure sodium (LPS), have no colour rendering capability at all. Others, such as high-pressure sodium (HPS), have a limited capability, while yet others, such as metal halide (MH) and some light-emitting diodes (LEDs), can be attractive for a wide range of materials including human skin. How the environment and the people in it appear can affect peoples' reactions to a space. Depending on how it is done, lighting useful for pedestrians can, itself, be a thing of beauty. Even if it is not, depending on the features of the environment available, lighting of buildings, parks, fountains, etc., can contribute to the creation of an exciting and attractive night-time environment.

11.3 LIGHTING CRITERIA

It should be apparent from the previous list of desires that lighting for pedestrians should involve much more than lighting for drivers because the area to be considered is much larger than just the road surface. This is why recommendations intended primarily for pedestrians are given in terms of illuminance. It is only where there is a well-defined direction of view that it is feasible to use luminance as a basis for recommendations, for example, for drivers on traffic routes.

In the United Kingdom (BSI, 2003), the minimum maintained average horizontal illuminances recommended for residential roads, cycle tracks and footpaths, where the lighting is intended primarily for pedestrians, range from 2 to 15 lx, in six classes (Table 11.1). The choice of class is based on the level of traffic flow, the crime rate and the environmental zone (see Section 15.6.3). The highest illuminances are recommended for urban areas where the traffic flow and crime rate are high. To ensure a reasonable level of illuminance uniformity, a minimum illuminance at any point is recommended for each class. A trade-off between illuminance and light source is also allowed. Specifically, if

TABLE 11.1
Illuminances Recommended for Residential Roads in the United Kingdom

Lighting Class	Minimum Average Horizontal Illuminance (lx)	Minimum Point Horizontal Illuminance (lx)
S1	15	5.0
S2	10	3.0
S3	7.5	1.5
S4	5.0	1.0
S5	3.0	0.6
S6	2.0	0.6

Source: British Standards Institution (BSI), BS EN 13201-2:2003, *Road Lighting – Part 2: Performance Requirements*, BSI, London, U.K., 2003.

the light source to be used has a Commission Internationale de l'Eclairage (CIE) general colour rendering index (CRI) of 60 or more, then the lighting can be reduced by one class. This is an attempt to reduce energy consumption while maintaining the brightness of the scene. LPS and HPS light sources, which are widely used for residential roads in the United Kingdom, have higher luminous efficacies than better colour rendering light sources like MH and white LEDs, so whether or not reducing the illuminance by one class actually saves energy depends on the light source being replaced and what it is replaced with, as well as the reduction in illuminance. As for brightness, there is no doubt that light sources that have greater power at the short-wavelength end of the visible spectrum produce a perception of higher brightness at the same illuminance (see Section 6.2.2.4). This means the loss of brightness associated with a reduction in illuminance can be offset by choosing a light source with more short-wavelength power. Finally, to control disability glare, the maximum luminous intensity per 1000 lumens from the luminaires should be less than 200 cd/klm at 80° and less than 50 cd/klm at 90° from the downward vertical.

It might be thought, justifiably, that these recommendations fail to address many of the desires of pedestrians. They certainly provide a basis for ensuring safe movement along a road and provide some guidance about where the road goes, but they do not directly offer guidance on how to illuminate the surrounding environment and avoid discomfort glare. The problem for anyone writing lighting recommendations is that the best means to illuminate the surrounding environment will depend on the opportunities presented by the specific site. This is where the lighting designer comes in. Anyone with a basic knowledge of lighting and appropriate software can design lighting for residential roads that meets the above criteria, but it takes someone with an eye for the site and an aesthetic sense to create an attractive and comfortable installation which also meets the lighting criteria. Unfortunately, most lighting of residential roads is not done by such paragons. Rather, residential roads are routinely lit so as to meet the previous criteria, any lighting of the surroundings being a function of the luminous intensity distribution of the chosen luminaire and reflected light. It is only for prestigious parks and roads that the full potential of lighting to reveal the beauty of the site will be employed.

The situation is similar in other countries. In Australia, lighting recommendations for local roads are divided into five classes (Standards Australia, 2005). The minimum average horizontal illuminance ranges from 0.5 to 7.0 lx (Table 11.2), values considerably lower than those recommended in the United Kingdom for equivalent locations. The choice of class depends on the level of pedestrian activity, the risk of crime and the prestige of the road. Higher levels on these three concerns lead to high illuminances. For classes P1 to P3, these illuminances apply to the pavement only, but for classes P4 and P5, the illuminances apply to the full width of the road from property boundary to property boundary. To control the illuminance uniformity, there are two recommendations. The first is a minimum horizontal illuminance at any point, ranging from 0.07 to 2 lx. The second is a maximum horizontal illuminance ratio (maximum/average) of 10, applicable to all classes. There is also a minimum vertical illuminance given for the three highest classes, ranging from 0.3 to 2 lx (Table 11.2). This is a valuable criterion as vertical illuminance is important for revealing the face of someone approaching. There is also an allowance for light spectrum but only for classes P4 and P5, that is, for the lowest illuminances where vision will be well into the mesopic range. In this case, the adjustment takes the form of a forced reduction in the light output of LPS and HPS lamps from their published values. Specifically, the light output of LPS lamps is reduced to 50% of the published value. For HPS, the reduction is to 75%. This is done to discourage the use of these poor colour rendering light sources, most lighting of residential roads in Australia already being by white light sources such as fluorescent and mercury vapour.

Most other European Union countries use the same lighting criteria as are used in the United Kingdom (Table 11.1) but without any adjustment for light spectrum. In the United States, the minimum maintained average illuminance for local roads,

TABLE 11.2
Illuminances and Illuminance Uniformity Recommended for Use in Australia and New Zealand

Lighting Class	Minimum Average Horizontal Illuminance (lx)	Minimum Point Horizontal Illuminance (lx)	Maximum Horizontal Illuminance Uniformity Ratio (Maximum/Average)	Minimum Point Vertical Illuminance (lx)
P1	7.0	2.0	10	2.0
P2	3.5	0.70	10	0.7
P3	1.75	0.30	10	0.3
P4	0.85	0.14	10	—
P5	0.50	0.07	10	—

Source: Standards Australia, *Lighting for Roads and Public Spaces. Part 3 Pedestrian Area (Category P) Lighting – Performance and Installation Design Requirements*, AS/NZS 1158.3.1:2005, Standards Australia, Sydney, Australia, 2005.

which include roads designed for access to residential property, ranges from 3 to 9 lx, higher values being used where pedestrians are more likely to come into conflict with vehicles (IESNA, 2005a). In this case, the minimum illuminance uniformity, expressed as minimum/average, is 0.17. There is no allowance made for the light source used.

All these countries use horizontal illuminance on the pavement as a criterion but differ markedly in the range of values chosen, from Australia with a range of 0.5–7 lx to European Union countries with a range of 2–15 lx. Such variation in lighting recommendations in different countries is not unusual as they are essentially matters of consensus, involving the consideration of many factors (Boyce, 1996), and different countries give different emphasis to different factors. It is also important to note that these recommendations are minima. While the minima are likely to be used by local authorities committed to a green agenda and saving money, the same cannot be said for many commercial enterprises. The economic consequences for a shopping mall if the car park were to be perceived as dim and possibly dangerous are too serious to risk using the minima. As a result, it is common to find car parks around shops and supermarkets lit to illuminances well above the minima.

11.4 LIGHTING FOR SAFE MOVEMENT

11.4.1 Collisions, Trips and Falls

The most fundamental reason for lighting a street is to enable people to see obstacles on their path ahead and thereby avoid bumping into them or tripping over them. That this is a real hazard is apparent from studies of accidents in car parks. Box (1981) examined car park accidents in the United States. He found that about two-thirds involved a moving vehicle hitting a parked vehicle but only 1% involved a vehicle hitting a pedestrian. Accidents involving pedestrians are much more likely to be associated with tripping, slipping and falling while moving through the car park (Monahan, 1995).

One way to assess how much light is necessary to enable people to move safely is to measure how long it takes for people to move through a furnished space. Boyce (1985) did this in a study of escape lighting. In this study, people sat at a desk in the middle of a large open-plan office furnished with chairs, desks and large filing cabinets arranged so that there was an open corridor down the centre line of the office to the exit door. When the normal room lighting was switched off leaving only the escape route lighting, the participants had to find their way through the furnishing to the corridor and then to the exit door. The normal lighting of the office delivered an average illuminance of 580 lx on the floor of the furnished area and 485 lx on the floor of the corridor. The incandescent escape lighting delivered four reasonably uniform illuminances on the floor of both areas, mean values ranging from 0.012 to 6.67 lx. Figure 11.1 shows the mean times taken to move through the office area and along the corridor to the exit door under the different illuminances. Above a mean floor illuminance of about 1 lx, the time taken to move from the desk at which they were seated to the exit door is approaching saturation as the mean time taken to make the same journey under the normal room lighting is about 15.9 s.

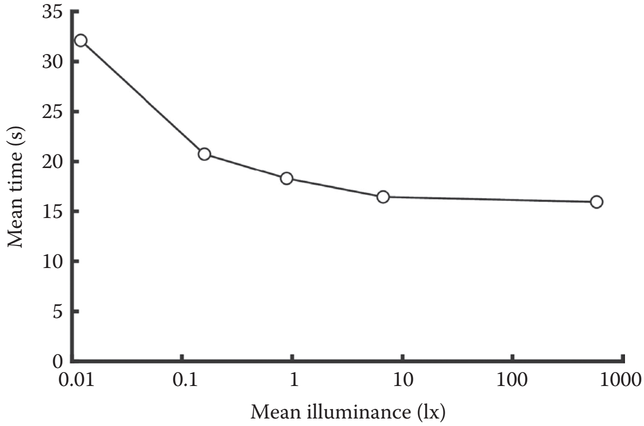


FIGURE 11.1 Mean time taken to move from a desk in a large open-plan office to the exit door plotted against the mean illuminance on the floor. (From Boyce, P.R., *Lighting Res. Technol.*, 17, 51, 1985.)

Another way to evaluate the necessary illuminance for safe movement is to examine the manner of movement. In the experiment described above, IR video recordings were made of the way people moved through the office. The movements were divided into four classes: smooth steady movement, hesitant movement, very hesitant movement and confused movement. Smooth steady movement was characterized by a constant velocity with no touching of objects as they were passed. Hesitant movement was shown by slowing down on changing direction and reaching out with a hand to touch furniture. Very hesitant movement involved very wide variations in velocity and touching surfaces to feel the way. Confused movement was shown by changes and reversals of direction and continual touching to feel the way. All the people moving through the office at a mean illuminance of 0.85 lx showed smooth steady movement, a finding that supports the conclusion that an illuminance more than 1 lx is all that is necessary for safe movement.

Now, it may be objected that these results were obtained in an office rather than on the street. The counter argument is that it was a large furnished open-plan office (30 m by 16 m) with several different paths to the corridor, so leaving the office was like walking along a pedestrianized street. Further, the upper end of the illuminance range studied was representative of those recommended for residential streets. A more serious objection is that the people attempting to move through the space immediately after the normal lighting was extinguished would have been misadapted. This is true in the sense that while neural adaptation would have been complete within a second, the same cannot be said for photochemical adaptation (see Section 2.3.1). Given more time for adaptation, it is likely that smooth steady movement would have been achieved at the lower illuminances. This implies that the 1 lx identified as being necessary for safe movement by this study is a conservative estimate.

Another objection to this study is that the objects to be avoided, for example, desks and chairs were large and the participants could reasonably assume that the floor was unobstructed. However, in real streets, this may not be so. Fotios and Cheal (2009) carried out a laboratory study designed to measure the minimum height of a raised section of pavement that could be detected off-axis in a single glance under different illuminances provided by different light sources. The observer was asked to fixate a point 120 mm above a flat plane representing the pavement, using only one eye. Six cylindrical blocks of the pavement could be made to rise above the level of the pavement to a fixed position before being presented for 300 ms, this being the typical time for a single eye fixation. The six positions were all off-axis, up to 10.7° below and 42° to the right of the fixation point. Three different illuminances were used: 0.2, 2.0 and 20 lx, provided by an overhead light box to ensure diffuse lighting. Three different light sources were used to provide these illuminances: one HPS and two types of MH. For each presentation, the subject simply had to say if the pavement was raised and, if so, which block was raised. By doing this for a range of heights, it was possible to plot the percentage of presentations when a block height was detected under a fixed illuminance and light source by young (<45 years) and old (>60 years) observers. A four-parameter logistic equation fitted through the data made it possible to determine the block height which could be detected 50% of the time. Figure 11.2 shows the mean block height for 50% detection probability for four obstacles plotted against illuminance for the three light sources and both age groups. There are a number of interesting features of these results. The first is that there is a non-linear effect of illuminance as would be expected from what is known about visual performance (see Section 4.3.5). The non-linear effect is shown by the fact that the increase in block height required for 50% detection consequent on a reduction from 20 to 2.0 lx is much less than that from 2.0 to 0.2 lx. This suggests that some of the Australian recommendations for residential roads may be too low. The second is that

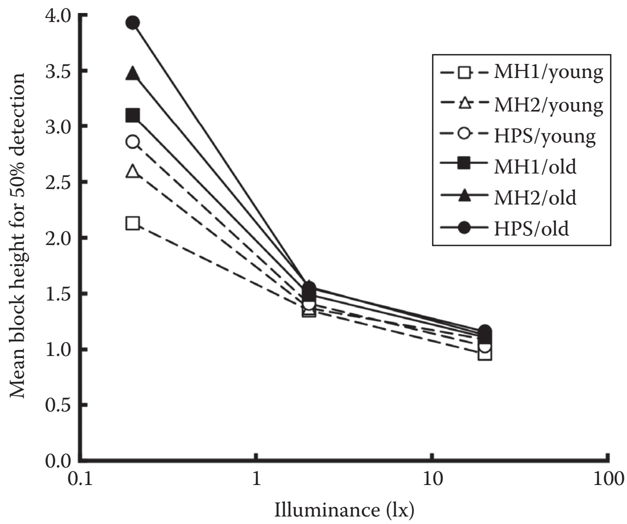


FIGURE 11.2 Mean block height for 50% detection probability of four blocks seen off-axis by young (<45 years) and old (>60 years) subjects for three different lamp types: two MHs (MH 1 and 2) and one HPS discharge, plotted against illuminance on the pavement. (After Fotios, S. and Cheal, C., *Lighting Res. Technol.*, 41, 321, 2009.)

the light source used has an effect, but only at the lowest illuminance (0.2 lx). At 20 and 2.0 lx, there are no statistically significant differences between the light sources. Where the light source does have an effect, this is related to the scotopic/photopic ratio (see Section 1.6.4.5). This suggests that it is not until the visual system is well into the mesopic state that light spectrum has a serious effect on off-axis visual performance. Further, given that the minimum illuminance recommended for lighting residential roads in the United Kingdom is 2 lx, these findings suggest that the reduction of one class allowed for using a light source with a CIE general CRI greater than 60 has to be based on something other than visual performance. The third is that the young age group can see smaller block heights than the old age group for all three light sources at 0.2 lx but there is no statistically significant difference between the age groups at 20 lx. Again, this is to be expected given the increased absorption and scattering of light in the eye with increasing age (see Section 13.2).

Fotios and Cheal (2013) followed up this work using the same apparatus and methodology with more illuminances but with only young subjects and one light source, HPS. Figure 11.3 shows the mean block height for 50% detection probability for the young age group and HPS lighting from the earlier study and from the 2013 study. The agreement between the two studies at the same illuminances is very encouraging, and the additional illuminances clarify the shape of the performance curve. However, these data have two limitations for practical application.

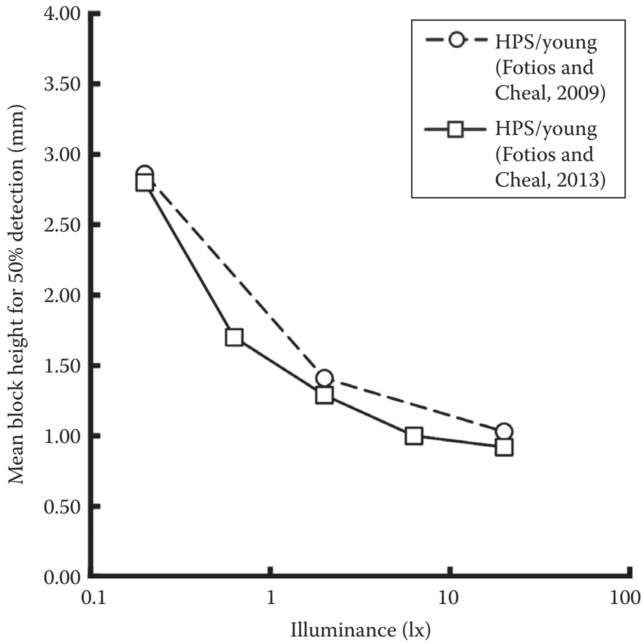


FIGURE 11.3 Mean block height for 50% detection probability of four blocks seen off-axis by young subjects under HPS lighting plotted against illuminance on the pavement. Also shown are the mean block heights for young subjects under HPS from Figure 11.2. (After Fotios, S. and Cheal, C., *Lighting Res. Technol.*, 44, 362, 2013.)

The first is that no one is interested in the block heights which 50% of people fail to detect. For practical application, what is required is the block height which 95% of people detect in a single fixation. Fortunately, this can be estimated from the best-fitting four-parameter logistic equation through the data. The other limitation is that the block height is measured in millimetres but it is not the absolute height that matters. What matters for visibility is the visual size, that is, the angle subtended by the block at the eye. Given the dimensions of the apparatus, it is possible to convert the absolute block height into angle subtended at the observer's eye. Figure 11.4 shows the angle subtended in minutes of arc for the block height that was detected on 95% of presentations plotted against illuminance. An illuminance of about 2 lx is identified as where performance starts to decline.

The next question that needs to be addressed is whether such visual angles are of concern. In the United Kingdom, local authorities tend to treat paving height misalignments of about 25 mm as needing urgent repair as they are at risk of legal action should someone trip and injure themselves (Fotios and Cheal, 2013), but how far ahead do people look when walking along the pavement? There is no established answer to this, but assuming a step length of 600 mm and a fixation point from 2 to 10 steps ahead, Fotios and Cheal (2013) estimate that the angle subtended by a 25 mm step in the pavement at the pedestrian eye will range from 28.2 min arc to 13.5 min arc. An examination of Figure 11.4 shows that such angles can be detected on 95% of occasions under illuminances ranging from 0.10 to 0.62 lx, respectively. There can be no doubts about adaptation in this study, yet the results suggest a minimum illuminance in the range 0.1–1.0 lx. This is of the same order as the lowest illuminances recommended in Australia and somewhat less than those used in the United Kingdom or the United States.

It is important to appreciate that the results discussed previously are a very small sample of those that could be obtained by varying the size, contrast and location and presentation time of the obstacle to be detected. Given that in the real world

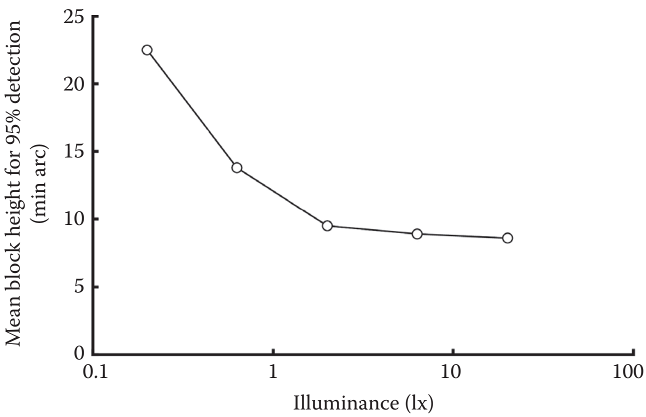


FIGURE 11.4 Mean block height for 95% detection probability of four blocks seen off-axis by young subjects under HPS lighting plotted against illuminance on the pavement. The block height is expressed as the visual angle subtended at the eye in minutes of arc. (After Fotios, S. and Cheal, C., *Lighting Res. Technol.*, 44, 362, 2013.)

obstacles likely to cause collisions, trips and falls will vary widely in size, contrast and location and have to be detected by people of different ages who will be looking at many different things but may not be paying attention to any of them, the limiting illuminances identified should be taken as indicative rather than definitive.

11.4.2 Crossing the Road

Anyone walking down the street is likely at some point to have to cross the road. Pedestrians crossing the road are exposed to a risk of death or injury by collision with high-momentum vehicles, particularly in winter when the hours of darkness are longer (Papadimitrou et al., 2009). In the United Kingdom, in 2005, 21% of all the people killed in road accidents were pedestrians (Eurotest, 2008). This is why special crossing points are identified where pedestrians have priority over vehicles. Pedestrians who do not use these crossing points are at much greater risk of death or injury than those who do. In the United Kingdom, in 2005, the number of pedestrians killed or seriously injured on a pedestrian crossing was only 11% of the total number of pedestrians killed or seriously injured (Eurotest, 2008).

There are two types of pedestrian crossings: those associated with traffic signals where the signals are arranged so as to give priority to vehicles and pedestrians at different times and those without traffic signals where a pedestrian waiting to cross or actually on the crossing has priority over vehicles at all times. The signal-controlled crossings are primarily a feature of urban areas where traffic volumes, both vehicular and foot, are high. The crossings without traffic signals are most frequently found in suburban areas where traffic of both types is lighter. To minimize the danger of using either type of pedestrian crossing, care has to be taken with location so that the driver's view of the crossing and the pedestrian's view of traffic are not obstructed, and appropriate warning signs and markings have to be used to identify it as a pedestrian crossing.

Lighting is sometimes used to emphasize the presence of a crossing and to increase the visibility of a pedestrian on the crossing at night. In both the United Kingdom and the United States, pedestrian crossings are considered as a conflict area defined as an area where vehicle and pedestrians come into conflict. In the United Kingdom, the recommendations for such areas are given in terms of a maintained average horizontal illuminance and cover a range of 7.5–50 lx, with a minimum overall illuminance uniformity of 0.4 (BSI, 2003). In the United States, for crossings associated with intersections in high-pedestrian-conflict areas, the recommendations are a maintained average horizontal illuminance of 20 lx, a horizontal illuminance uniformity ratio of 0.25 and a maintained minimum vertical illuminance of 10 lx at a height of 1.5 m. (IESNA, 2005a). For crossings associated with intersections in low-pedestrian-conflict areas, the recommendations are a maintained average horizontal illuminance of 2 lx, a horizontal illuminance uniformity ratio of 0.10 and a maintained minimum vertical illuminance of 0.6 lx. For crossings separated from intersections, a maintained average horizontal illuminance of 34 lx is recommended with a maintained minimum horizontal illuminance uniformity ratio of 0.33. Curiously, there is no recommendation for vertical illuminance for these crossings.

In both countries, where a pedestrian crossing is close to a junction or roundabout the lighting is designed as part of the wider conflict area but where it occurs in isolation as, for example, halfway along one side of a city block but where people wish to cross the road, there are two possibilities for lighting. One is to use the normal lighting of the traffic route but with the road lighting luminaires arranged so that the crossing is positioned at the midpoint between luminaires. The other is to supplement the road lighting with additional lighting. The supplementary lighting approach is recommended when the average road surface luminance is less than 1 cd/m^2 or the crossing is located on a bend or on the brow of a hill. The supplementary lighting should illuminate the crossing to a higher horizontal illuminance than that used to produce the average road surface luminance of the road approaching the crossing. The supplementary lighting should also have a strong vertical component to ensure that pedestrians are positively illuminated, which is why it is recommended that where conventional road lighting is used, the crossing should be at the midpoint between the luminaires.

Another possibility to consider is light spectrum. Supplementary lighting of any type improves the conspicuity of the crossing by increasing its brightness relative to the rest of the road, but using a light source of a different colour is even better. This increases the conspicuity of the crossing further because it adds another dimension on which the crossing differs from its surroundings. Janoff et al. (1977) report a study in which LPS lighting was installed over pedestrian crossings on roads that were lit by other light sources. As would be expected, the increased illuminance on the crossing increased the distance at which a target on the crossing could be detected by an approaching driver, but observations also suggested safer behaviour by both drivers and pedestrians. This use of a different colour of light is part of the recipe for better pedestrian crossing lighting developed by Freedman et al. (1975).

Even when light sources of the same light spectrum as the road lighting are used, the outcome of supplementary lighting is a bright stripe of light over the crossing and a higher vertical illuminance on pedestrians using the crossing. The benefits of this are evident in a study by Hasson et al. (2002). In this study at two mid-block crossings in an American city, the ability of observers sitting in a car 82 m away to detect the correct number of pedestrian-sized cutouts near or on the crossing was measured, the cutouts having a diffuse reflectance of 0.18. The crossing was lit using either conventional road lighting giving a road surface luminance of less than 2 cd/m^2 and producing vertical illuminances in the range 8–11 lx or with supplementary lighting resulting in a vertical illuminance at the crossing of 40 lx. The car in which the observers sat used low beam headlamps. Table 11.3 shows the percentage of presentations in which the drivers were able to detect fewer than, more than or the correct number of pedestrian cutouts in 2 s. It is evident that the supplementary lighting improves the ability to quickly detect the correct number of pedestrians, although much more at one site than the other. Whether this improvement is due to the change in light distribution implied by the emphasis given to vertical illuminance or the general increase in the amount of light in the area of the crossing is an open question that will not be resolved until the effects of such changes on the luminance contrasts presented by pedestrians are investigated. How important luminance contrast is to visibility can be seen in a study by Edwards and Gibbons (2007). In this study, people were asked to

TABLE 11.3
Percentage Detection of Fewer Than, More Than and the Correct Number of Pedestrian Cutouts for a 2 s Observation Period, for Two Pedestrian Crossing Sites Lit by Conventional Road Lighting with and without Supplementary Lighting

Site	Lighting Type	Fewer Than (%)	More Than (%)	Correct (%)
1	Conventional	50	17	33
1	Conventional + supplementary	10	10	80
2	Conventional	20	7	73
2	Conventional + supplementary	13	0	87

Source: Hasson, P. et al., Field test for lighting to improve safety at pedestrian crosswalks, *Proceedings of the 16th Biennial Symposium on Visibility and Simulation*, Transportation Research Board, Washington, DC, 2002.

drive a vehicle equipped with halogen headlamps over a closed test track and report when they detected a pedestrian on a crossing. The test track was lit by road lighting producing four different vertical illuminances on the crossings. The pedestrian was clothed in white, denim or black hospital scrubs. Figure 11.5 shows the mean detection distances for the three different levels of clothing reflectance and four different vertical illuminances produced by HPS road lighting. It is clear that the reflectance of the clothing has a much greater influence on detection distance than vertical

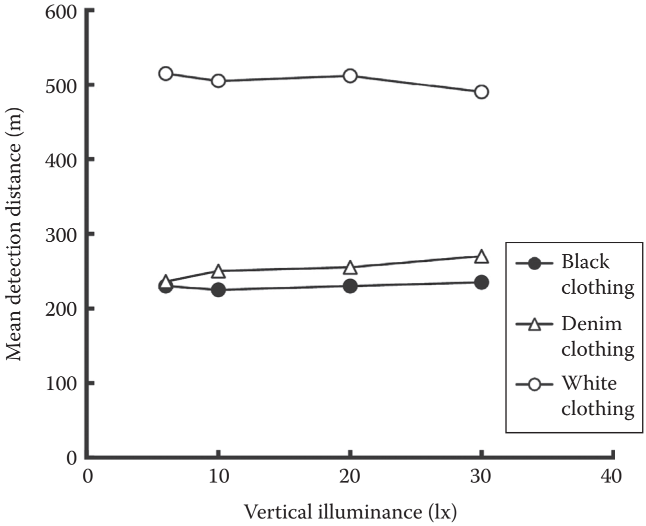


FIGURE 11.5 Mean detection distance (m) for pedestrians wearing black, denim or white clothing on pedestrian crossings plotted against the vertical illuminance at the crossing. (After Edwards, C.S. and Gibbons, R.B., *The Relationship of Vertical Illuminance to Pedestrian Visibility in Crosswalks, TRB Visibility Symposium*, Transportation Research Board, College Station, TX, 2007.)

illuminance over the range examined. These findings have two implications. The first is that those concerned about pedestrian safety should concentrate their efforts on persuading pedestrians to wear light-coloured clothing. The second is that the best form of lighting for pedestrian crossings will only be found when the effects on the stimuli presented to the visual system are evaluated.

One attempt to do this can be found in a study of the effect of four different methods of lighting a pedestrian crossing on the speed and accuracy with which observers could identify the direction in which adult and child silhouettes on the crossing were facing (Bullough et al., 2012a). The silhouettes were painted matte black with a reflectance of 0.08. The observers sat behind a set of car headlamps on low beam at a distance of 30.5 m (100 ft) from the crossing. The four lighting situations were (1) the low beam headlamps only, (2) two 60 W MH luminaires at 5.5 m (18 ft) height located at each end of the crossing and the car headlamps, (3) the same two MH luminaires but located 6.1 m (20 ft) from each end of the crossing in the direction of the observers and the low beam headlamps and (4) two bollard luminaires located 2.1 m (7 ft) from of each end of the crossing in the direction of the observers and the low beam headlamps. Lighting condition (2) maximizes the horizontal illuminance across the crossing. Lighting condition (3) maximizes the vertical illuminance across the crossing and is based on current practice. Lighting condition (4) uses two bollards developed from linear fluorescent wall washer luminaires and aimed at the centre of the crossing. The concept behind these bollards is to provide a high vertical illuminance on any object on the crossing but very little light on the road immediately ahead or behind the crossing (Bullough et al., 2010). This light distribution maximizes the luminance contrast of a pedestrian seen against the road. The accuracy of identifying the direction the silhouette was facing was always high, 99% correct for the adult and 96% for the child, but there were statistically significant differences in the time taken to identify the direction facing for the different lighting conditions. Figure 11.6 shows the mean identification times for the adult and child figures seen under the four lighting conditions. There is a statistically significant interaction between silhouette size and lighting condition. Specifically, the direction of the adult silhouette is identified more quickly than that of the child silhouette for all lighting conditions, apart from condition (4) where they are not statistically significantly different. Interestingly, lighting condition (3), which is based on current practice, is not statistically significantly different from condition (1), which has only low beam headlamps, but lighting condition (4) is particularly for the child.

A plausible basis for understanding these results is to assume that it is the highest luminance contrast of the silhouettes that people use to identify direction. The highest luminance contrasts occur for the arms or feet of the figures, depending on their location. The sizes and luminance contrasts of the arms or feet under the different lighting conditions were used to calculate the relative visual performance (RVP) for the two silhouette types based on the RVP model (see Section 4.3.5). Figure 11.7 shows the calculated RVP plotted against the mean identification time. The correlation coefficient associated with the best-fitting line through the data is 0.88.

Clearly, there is still something to be learnt about the best method for lighting a pedestrian crossing and the most effective approach to identifying the method that makes someone on the crossing most visible. This means considering the

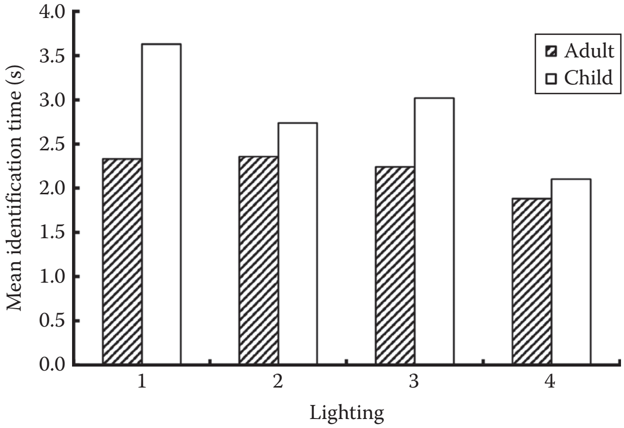


FIGURE 11.6 Mean time taken to identify the direction black adult and child silhouettes were facing on a pedestrian crossing under four different lighting conditions: (1) low beam headlamps only, (2) two 60 W MH luminaires located at each end of the crossing and the car headlamps, (3) the same two MH luminaires but located 6.1 m (20 ft) from each end of the crossing in the direction of the observers and the low beam headlamps and (4) two bollard luminaires located 2.1 m (7 ft) from each end of the crossing in the direction of the observers and the low beam headlamps. (After Bullough, J.D. et al., Evaluation of visual performance from pedestrian crosswalk lighting, *Annual Meeting of the Transportation Research Board*, TRB, Washington, DC, 2012a.)

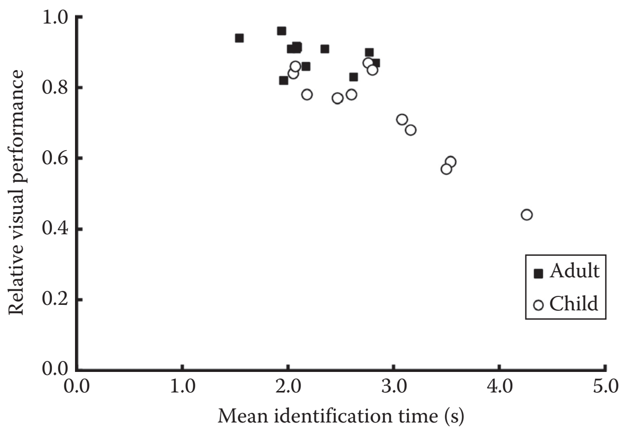


FIGURE 11.7 The RVP for identifying the direction black adult and child silhouettes were facing on a pedestrian crossing plotted against the mean identification times. The RVP values are based on the visibility of the arms and legs. (After Bullough, J.D. et al., Evaluation of visual performance from pedestrian crosswalk lighting, *Annual Meeting of the Transportation Research Board*, TRB, Washington, DC, 2012a.)

stimuli provided to the visual system such as visual size, luminance contrast, colour difference and adaptation luminance. Lighting cannot do much about visual size but it can have an effect on the other three. Light distribution influences luminance contrast, light spectrum affects colour difference and the amount of light determines the adaptation luminance. Further, the results of Bullough et al. (2012a) suggest that the

RVP model (Rea and Ouellette, 1991) can be used to integrate the effects of all these stimuli. Determining the individual stimuli created for the visual system, or even their integrated effect through RVP, is likely to be a much more fruitful approach than examining simple photometric variables such as illuminance. Ultimately, lighting recommendations have to be expressed through photometric variables because this is what people designing lighting systems use but those photometric variables and their values need to be derived from an understanding of the stimuli presented to the visual system and their consequences for visual performance.

There can be little doubt that supplementary lighting of pedestrian crossing can be designed that increases both the visibility and conspicuity of anything on the crossing, but that is not the complete answer. To be really useful, what drivers need to know is not only that they are approaching a pedestrian crossing but also that it is in use. Van Houten et al. (1998) examined the effectiveness of a combination of signs on driver behaviour. He found that simple signs indicating the presence of a pedestrian crossing had little effect on drivers but a combination of a sign indicating 'stop when flashing' and an overhead flashing beacon activated by the pedestrian was effective in reducing pedestrian/vehicle conflicts. Another approach, that of in-road warning lights triggered either manually or automatically by the pedestrian, had similar effects. A series of before and after studies have shown a limited number of effects on pedestrian behaviour but much more significant effects on drivers (Arnold, 2004). Specifically, the percentage of drivers who gave way to pedestrians increased, as did the distance from the crossing at which drivers braked, while the speeds at which vehicles approached the crossing were decreased. Consequently, pedestrian waiting time before crossing and the percentage of times a pedestrian on the crossing had to run to avoid approaching traffic were both reduced.

The message from such findings is clear – lighting has an essential but limited role to play in making pedestrian crossing safer places. Enhancing the conspicuity of the crossing and the visibility of pedestrians on and near a crossing by means of special lighting is useful at night but still relies on the driver searching the crossing and its environs before deciding if any action is necessary. To significantly improve the safety of pedestrians using crossings by day and night, it is also necessary to signal when there are pedestrians on the crossing or waiting to use the crossing. This can be done by signals triggered manually by the pedestrians or automatically by sensors. Such a system should be more effective because it would warn approaching drivers about an actual conflict rather than a potential conflict.

11.5 LIGHTING FOR SECURITY

Security can have many different meanings, from the overused excuse for intrusive government activities and, national security, to being simply a synonym for feeling safe. In the context of lighting for pedestrians, security is basically concerned with the latter. People who do not feel secure on the streets after dark are reluctant to use them. Indeed, significant numbers of women and the elderly avoid going outside after dark if they can (Heber, 2005). When this occurs, there are both economic and social consequences as well as deterioration in the quality of life for some. Lighting has a role to play in making people feel secure outside at night. That role is to make the surrounding scene visible. By making the surroundings visible, lighting can increase the distance at which a threat can be detected and increase the time available in which to frame an appropriate response (see Section 12.4 for a more extensive discussion). But lighting is not the only important factor in peoples' perceptions of outdoor lighting. Johannson et al. (2011) carried out a field assessment of a tree-lined and lit footpath and cycle path in a small town in Sweden by three groups likely to be sensitive to lighting: people with low vision, young women and the elderly. The footpath was lit using MH lamps, the lighting providing a mean horizontal illuminance on the footpath of 5.6 lx. After walking the path, each of the 81 participants was asked to complete a questionnaire from which a number of indices were extracted. The indices of interest here are perceived danger, brightness, environmental trust and hedonic tone. Table 11.4 shows the statements and descriptions related to each of these indices. Hierarchical multiple regression showed that perceived danger was related to brightness, gender, hedonic tone and environmental trust. People, particularly women, who saw the lighting as being unpleasant, unnatural and monotonous and of low brightness and who had a low level of environmental trust tended to consider the footpath more dangerous. These findings demonstrate that peoples' assessments of any lighting installation depend not just on the lighting but also on their personality and attitudes. Lighting designers cannot do much about personality and attitudes, but they can do something about the perception of brightness and hedonic tone, although the former is much easier to deal with than the latter.

TABLE 11.4
Statements and Descriptions of Lighting Used in the Construction of Indices Quantifying the Perception of an Urban Footpath

Index	Statement and Description
Danger	I would walk along this path unaccompanied.
	I would go a long way to avoid this place.
	I feel uneasy at this place.
	I would make haste to get away from this place.
	I have an unpleasant feeling at this place.
Brightness	Light
	Bright
	Brilliant
Environmental trust	I avoid walking alone through residential areas I am not familiar with.
	I find it uncomfortable to walk along lonely alleyways.
	I preferred to be accompanied when it is dark outside.
	I don't feel comfortable walking along narrow pavements.
Hedonic tone	Unpleasant
	Unnatural
	Monotonous

Source: Johansson, M. et al., *Lighting Res. Technol.*, 43, 31, 2011.

11.5.1 Spatial Brightness

As discussed in Section 2.5, brightness is strictly a perception associated with a self-luminous object, for example, a light source. However, people have no difficulty in talking about the brightness of a lighting installation even when it is totally indirect and the light sources are hidden from view. This is because in normal viewing conditions, the visual system is capable of perceptually separating the luminance pattern received at the retina into its components, the illuminance pattern and the reflectance pattern. It is believed that when people talk about the brightness produced by a lighting installation, they are reporting the amount of light in the space, that is, the illuminance pattern. To clarify this, a new term has been proposed – spatial brightness (Fotios and Alti, 2012). Spatial brightness is defined as 'a visual sensation related to the magnitude of the ambient lighting within an environment, such as a room or lighted street. This brightness percept encompasses the overall sensation based on the response of a large part of the visual field extending beyond the fovea. It may be sensed or perceived while immersed within the space or when the space is observed remotely but fills a large part of the visual field. Spatial brightness does not necessarily relate to the brightness of any individual objects or surfaces in the environment, but may be influenced by the brightness of these individual items'. There are three aspects of a lighting installation that are likely to affect the perception of spatial brightness: the level and distribution of illuminances and the light spectrum.

Boyce et al. (2000b) examined the role of illuminance on the perception of safety. Outdoor car parks were used as a suitable site for assessment because pedestrians can often be found in them, they occur frequently and they tend to be large and are lit uniformly so that a large area of the visual field will be involved. In total, 24 different car parks were visited by day and by night, 12 in an urban area and 12 in a suburban area. At each car park, a panel of people walked about in the car park before answering a questionnaire. The question of interest here is, 'How safe do you think it would be to walk alone in this parking lot?' The answer is given on a seven-point scale: 1 = very dangerous and 7 = very safe. Figure 11.8 shows the mean ratings on this question for the urban and suburban car parks, for day and night. It is evident from Figure 11.8 that the perceived safety of walking alone in the car parks during the day is higher in the suburban area than in the urban area. There are only two car parks in the urban area that approach the level of perceived safety of the suburban area by day, and these are the only two that have attendants. As for perceived safety when walking alone at night, Figure 11.8 shows that, for both urban and suburban car parks, lighting can bring that perception close to what it is during the day but cannot exceed it. The interesting question now is how illuminance relates to how close the perception of safety at night can be brought to what it is by day. Figure 11.9 shows the difference in ratings of safety when walking alone by day and night plotted against the median illuminance in the parking lot at night, for the urban and suburban parking lots. These results suggest that at a high enough illuminance, the difference in ratings of safety for day and night approaches zero. However, the approach to zero difference is asymptotic. Above 10 lx, the difference is less than one scale unit, and above 30 lx, the difference is less than half a scale unit on a seven-point scale.

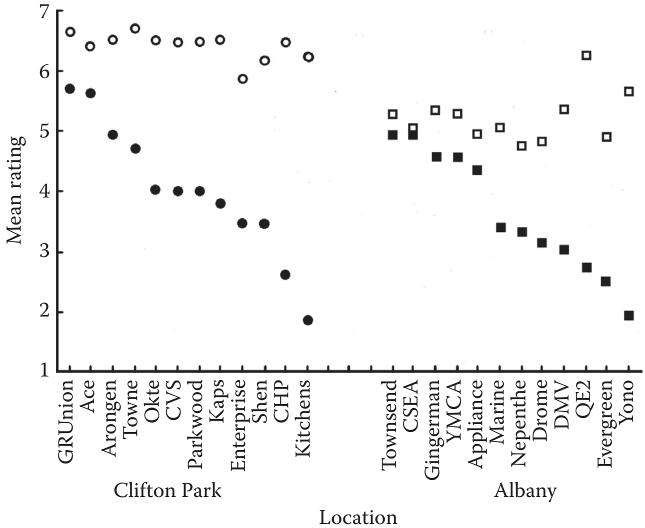


FIGURE 11.8 Mean ratings of perceived safety for walking alone in an open car park, by day and night, for car parks in Albany, NY (urban), and Clifton Park, NY (suburban). The car parks are presented in order of decreasing perceived safety at night (1 = very dangerous; 7 = very safe; ●, ■ = night, ○, □ = day). (After Boyce, P.R. et al., *Lighting Res. Technol*., 32, 79, 2000b.)

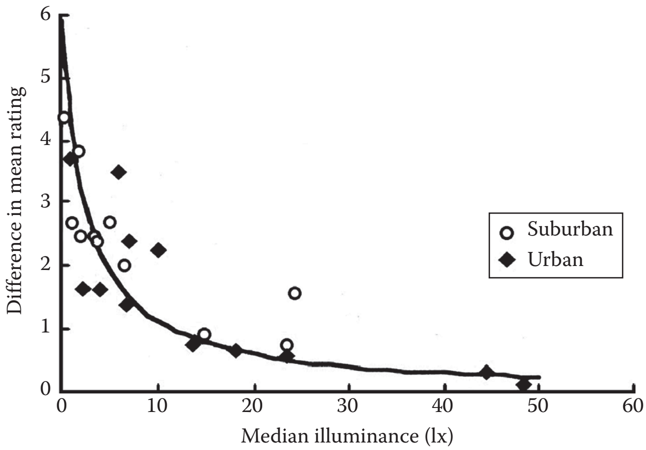


FIGURE 11.9 Difference in mean ratings of perceived safety for walking alone in an open car park, by day and night (day–night) plotted against median pavement illuminance for the car parks in Albany, NY (urban), and Clifton Park, NY (suburban). (After Boyce, P.R. et al., *Lighting Res. Technol*., 32, 79, 2000b.)

There are a number of limitations to this study, the most important being the fact that different lighting systems were used in different car parks. Some of these systems used different light sources and others had different light distributions depending on the luminaires used and their positions. Despite these differences, there can be little doubt that the illuminance on the car park is an important factor in determining people's perceptions of safety, but what about the effects of light distribution and light spectrum? To date, there has been no systematic study of how the light distribution might influence the assessment of safety when walking alone at night, although it clearly should, but there has been some work done on light spectrum. That light spectrum influences spatial brightness is well established, the reasons being the involvement of the visual colour channels in brightness perception and, in mesopic conditions, rod photoreceptor activity (see Section 6.2.2.4). Fotios and Cheal (2011b) carried out a study seeking to identify the best measures to predict how much illuminance could be traded off against light spectrum for equal spatial brightness, using side-by-side comparisons between two booths fitted with different light sources. The most accurate predictor was the ratio of the scotopic/photopic (S/P) ratios of the two light sources. Figure 11.10 shows the ratio of S/P ratios plotted against the illuminance ratio for equal brightness. To use this information, it is necessary to choose two light sources to compare. At the moment, for outdoor lighting, the market is divided between HPS and MH light sources although the use of LED light sources is rapidly increasing. For the HPS and MH light sources used by Fotios and Cheal (2011b), the ratio of S/P ratios is 3.46. For this ratio, Figure 11.10 suggests an illuminance ratio for equal spatial brightness of 0.80. A comparison between HPS and an LED light source shows an even larger ratio of S/P ratios and hence a lower illuminance ratio for equal spatial brightness which illustrates the potential for LED lighting, but care needs to be taken with this conclusion because LEDs can be manufactured with many different light spectra and, consequently, many different S/P ratios.

Given that both illuminance and light spectra can influence spatial brightness, it is reasonable to expect both to influence perceptions of safety. Rea et al. (2009a) carried out an experiment in the field in which people looked down an isolated road in a park setting lit in one direction by HPS and in the other by MH light sources. The luminaires containing the two types of light source produced similar

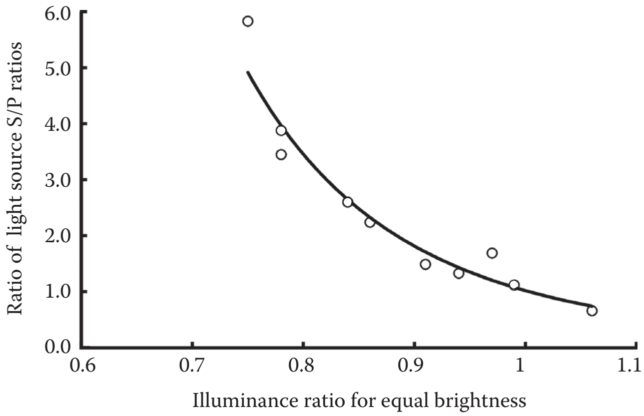


FIGURE 11.10 Ratio of scotopic/photopic ratios for two light sources plotted against the illuminance ratio for equal brightness for the same two light sources. (After Fotios, S.A. and Cheal, C., *Lighting Res. Technol.*, 43, 143, 2011b.)

horizontal illuminance distributions. The observers were asked to look alternately in the two directions and answer three questions:

- Under which lighting do the objects and street appear brighter?
- Under which lighting would you feel safer walking at night?
- Under which lighting would it be more acceptable to sit, socialize and chat if you were at a street café?

A number of different illuminances in the range 5–15 lx were used for both light sources. The illuminance ratio for equal spatial brightness was found to be 0.79, very close to that obtained by Fotios and Cheal (2011b). As for the effect on the perception of safety, Figure 11.11 shows the percentage of observers considering the MH lighting to be safer plotted against the horizontal illuminance provided by the MH lighting relative to that provided by the HPS lighting. The horizontal illuminance provided by MH lighting for an equal perception of safety was 0.66 of that provided by HPS.

One of the doubts that haunt anyone seeking to transfer results to the real world is how well the findings will stand up once the strict controls used in scientific experiments are relaxed. Fortunately, for studies of the effects of light spectrum on perceptions of spatial brightness and safety, Knight (2010) carried out a series of assessments of street lighting in Navalcarnero, Spain, Eindhoven, the Netherlands, and St Helens, United Kingdom. In Spain and the Netherlands, HPS street lighting was replaced with MH lighting, the average horizontal illuminances being 82 lx (HPS) and 81 lx (MH) in Spain and 16.5 lx (HPS) and 14 lx (MH) in the Netherlands. In the United Kingdom, the light sources were changed in both directions, that is, from HPS to MH and reverse. The average horizontal illuminances were in the range 9.1–12.7 lx for the HPS lighting and 8.9–12.6 lx for the MH. Given the similarity

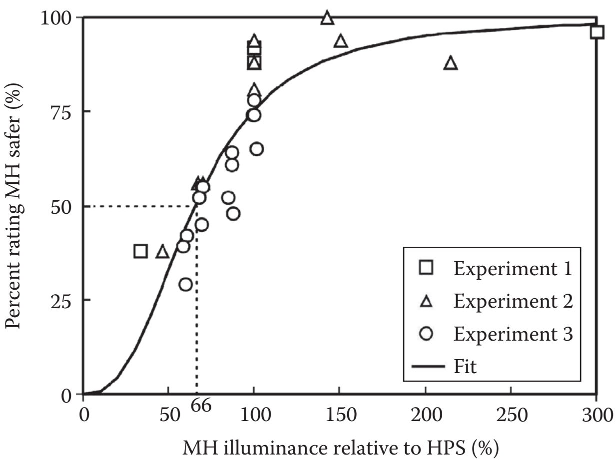


FIGURE 11.11 The percentage rating MH lighting as safer to walk under at night plotted against the horizontal illuminance for the MH lighting relative to that of the HPS lighting. (From Rea, M.S. et al., *Lighting Res. Technol.*, 41, 297, 2009a.)

of the average horizontal illuminances for the different light sources at the same site, it would be expected that the MH lighting would consistently be considered to be brighter and safer than the HPS lighting. This is what was found. It is encouraging that the direction and, to some extent, the magnitude of the effect of light spectrum on the perceptions of spatial brightness and safety have been confirmed in the field.

11.5.2 Visual Performance

So far, the approach to identifying the lighting conditions required for giving pedestrians a sense of security has been though increasing the perception of spatial brightness, but is that enough? The reason why spatial brightness appears to be effective in enhancing perceptions of safety is that to most people, it implies better visual performance. This, in turn, means that it should be possible to see finer detail at greater distances which gives more time in which to recognize a threat and to decide and act on an appropriate response. Therefore, another way to identify the lighting conditions required to ensure a perception of safety is to examine under what conditions an acceptable level of visual performance can be achieved. But what should be the task? One approach is to use basic visual functions that can be taken to imply finer discrimination. Simple threshold measures, such as visual acuity, become finer with increasing adaptation luminance up to luminances much higher than those conventionally used in outdoor lighting (see Figure 2.17). Measurements of visual acuity under road lighting conditions provided by different light sources have usually shown an increase in acuity as the luminance of the acuity chart increases but no effect of light spectrum (Boyce and Bruno, 1999; Fotios et al., 2005). This is what would be expected given that visual acuity is measured when directly viewing the target, so the fovea is the part of the retina used. The fovea contains few rods so there is no shift in spectral sensitivity in mesopic conditions. It is true that visual acuity has been shown to improve when the light spectrum leads to a smaller pupil size (Berman et al., 2006) but for this to occur, a large portion of the visual field has to be actively involved (see Section 7.3.2.2). In the measurements referred to in the previous discussion, it is likely that the luminance of the acuity chart background would be much higher than the road surface but this would only cover a small part of the visual field so any effect on pupil size would be small.

Another approach is to study the performance of simple, realistic tasks. This approach has been used to examine the ability to detect stimuli off-axis. Such studies have produced a consistent pattern showing that both illuminance and light spectrum are important to the detection of objects off-axis: the higher the illuminance and the greater the stimulation to the rod photoreceptors, the better the off-axis visual performance (see Section 10.4.3).

One realistic task that has been widely used as a basis for determining suitable lighting conditions for security outdoors is facial recognition. Rombauts et al. (1989) studied the ability to recognize a face from various distances. Following the work of Caminada and van Bommel (1980), semi-cylindrical illuminance was used as a measure of the lighting conditions. Semi-cylindrical illuminance is the average illuminance on the surface of an upright half cylinder. Figure 11.12 shows the relationship between the distance at which the observers were completely confident that

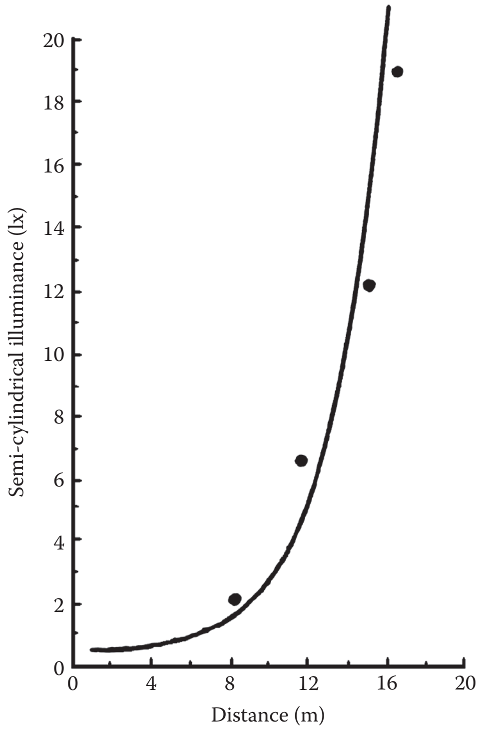


FIGURE 11.12 The semi-cylindrical illuminance on the face necessary for completely confident recognition plotted against distance. (After Rombouts, P. et al., *Lighting Res. Technol.*, 21, 49, 1989.)

they recognized the person they were approaching and the semi-cylindrical illuminance on the face of the person being approached. Rombauts et al. (1989) claim that confident face recognition is not possible beyond 17 m and that a semi-cylindrical illuminance on the face of 25 lx is sufficient to give confident identification at this distance. Obviously lower semi-cylindrical illuminances can be used if the confident recognition at shorter distances is acceptable. Hall (1966) claims that 4 m is close to the boundary of what is called the public space surrounding an individual and that anyone unexpectedly approaching closer will cause alarm. Rombauts et al. (1989) identify a minimum semi-cylindrical illuminance of 0.6 lx on the face as necessary to ensure confident identification at 4 m. This is all very interesting but it is of little use because semi-cylindrical illuminance is so rarely used. Fortunately, Rombauts et al. also found that people considered the lighting of facial features to be well balanced when the vertical/semi-cylindrical illuminance ratio was in the range 1.1–1.5. Assuming a desirable vertical/semi-cylindrical illuminance ratio of 1.3, their results convert to a vertical illuminance of 33 lx for confident face recognition at 17 m and 0.8 lx at 4 m.

Boyce and Rea (1990) examined the effects of different perimeter security lighting installations on people's ability to detect someone walking towards them and then to recognize them from a selection of four black and white photographs. The results obtained showed that the probability of detecting someone approaching reached 90% at a vertical illuminance on the person of 4–10 lx, the lower illuminance occurring when the person was approaching along a known path, while the higher illuminance occurring when the person could come from anywhere ahead of the observer. Higher illuminances are needed to approach 100% detection. A vertical illuminance of about 10 lx was sufficient to obtain 90% correct recognition of an approaching person. A higher vertical illuminance will allow a higher probability of recognition, but the possibility for improvement is limited. Interestingly, no significant difference in the ability to recognize faces under LPS and HPS light sources was found. This should not be too surprising as both light sources have limited colour properties and the observers were using black and white photographs as a reference.

Rea et al. (2009a) also carried out a facial recognition experiment which overcame these limitations. At their isolated road site, a person stood just behind either an HPS or an MH luminaire so that an illuminance of 8 lx was received on the face. Starting from a distance of 25 m, an observer walked towards this person carrying a DVD player showing eight digital colour photographs of young male people, one of which was of the person ahead. The observer was asked to stop when he could guess which of the eight possible people was present and then move forwards until certain about the identification. The mean distance at which the observers could guess the identity of the person ahead was 20 m, but for certainty, the distance was reduced to 12 m. This shows reasonable agreement with the results of Rombauts et al. (1989). Also, there was no statistically significant difference between either guess or certainty differences for the two light sources.

Such results suggest that colour information is not important for facial recognition. However, Knight (2010) showed statistically significant differences between light sources for the distance at which people could guess the identity of a national celebrity from a picture and then the distance at which they were confident about that identity. Unfortunately, there was no consistency as to which light source produced greater distances. Thus, the role of light spectrum in facial recognitions is not clear. This may not matter because others have suggested that facial recognition is not itself an important task for determining suitable lighting conditions for pedestrians (Fotios and Raynham, 2011). The concern is that most of the time people met on the street are strangers so there is no possibility of recognition and, even if there is, facial recognition is not what matters. Fotios and Raynham (2011) suggest that what matters to a pedestrian out at night is being able to identify the intent of people approaching. It can be argued that being able to see enough detail to recognize a face from a display of alternatives is closely related to being able to recognize the intent behind a facial expression, but if this is so, the person approaching will be quite close before a decision about a response can be made. Possibly, people use body language and visual and auditory cues to identify intent at greater distances. One study that addresses cues other than facial appearance asked observers to perform a number of tasks in a large, rectangular car park lit by luminaires fitted with either HPS or MH light sources (Boyce and Bruno, 1999). While doing the tasks, the subjects were seated in a car looking down the length of one of the driving aisles, wearing and not wearing grey wrap-around glasses with a transmittance of 0.10. Figure 11.13 shows the result of asking the observer to identify objects carried by a person in

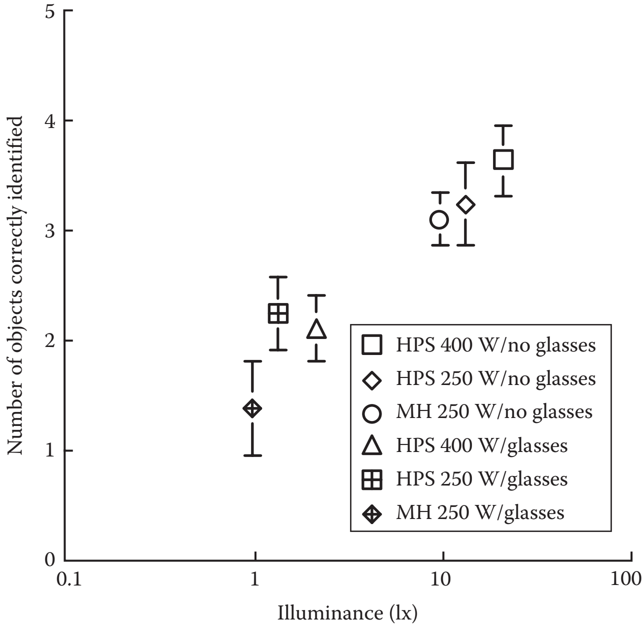


FIGURE 11.13 Mean number of objects correctly identified plotted against the mean illuminance on the pavement. The error bars are standard errors of the mean. Data are given for different combinations of HPS and MH lighting seen with the naked eye (no glasses) and through low-transmittance glasses (glasses). (After Boyce, P.R. and Bruno, L.D., *J. Illum. Eng. Soc*., 28, 16, 1999.)

the parking lot. Under each lighting condition, the subjects were asked to identify whether a person about 10 m away was carrying a metal ruler, a hammer, a spanner, a spray can, a screwdriver, a torch, a beer bottle, a gun, an umbrella, a knife or a pair of scissors. The mean number of objects correctly identified out of a maximum possible of five is closely related to the illuminance in the parking lot, independent of light spectrum. From Figure 11.13, it is clear that illuminances higher than those recommended for residential roads are needed to accurately identify such objects, even when they are only 10 m away.

From the previous discussion, it should be clear that different tasks lead to different answers about desirable lighting conditions for pedestrians. Thus, it is unlikely that any progress will be made in determining the lighting conditions needed for security until some agreement has been reached on what it is that pedestrians need to be able to see in order to assess a place and a situation.

11.6 LIGHTING, COMFORT AND ATTRACTION

Pedestrians using the streets at night want to feel comfortable. Unfortunately, being asked if you feel comfortable is ambiguous. To one person, being comfortable might be taken to mean that he or she feels at ease and is unconcerned about their security. To another, it could mean that there is nothing that makes them shade the eyes or look away. In a series of field studies, Knight (2010) made it explicit that comfort referred to feelings of ease/unease and found that streets lit to similar illuminances by MH light sources were considered more comfortable than the same streets lit by HPS light sources, probably because of the perception of greater spatial brightness.

Boyce et al. (2000b) used a different approach by specifically asking about a possible cause of discomfort, glare. In this study, two different groups of people visited 12 different streets in New York City and 15 in Albany, the capital of New York State. After walking along each street, the people were asked to rate the lighting of the street on a series of five-point scales labelled bad/good, bright/dark, uneven/even, comfortable/uncomfortable, glaring/not glaring, extensive in area/limited in area and poorly matched to site/well matched to site. The ratings given on the bright/dark, comfortable/uncomfortable and extensive in area/limited in area scales were reverse scored so that a rating of 5 corresponded to a perception that the lighting was good, bright, even, comfortable, not glaring, extensive in area and well matched to site. Conversely, a rating of 1 corresponded to a perception that the lighting was bad, dark, uneven, uncomfortable, glaring, limited in area and poorly matched to the site. Figure 11.14 shows the mean ratings given on these scales for all 27 streets. Clearly, there are streets in both locations that are well lit and others that are not. This should not be a surprise because the streets were deliberately chosen to cover a wide range of conditions. What is more interesting is that the rating of glaring/not glaring shows a very different trend from all the other scales. All the other scales change together indicating that good lighting for city streets is perceived to be bright, even, extensive in area and well matched to the site. The glaring/not glaring scale is very different from all the others. None of the streets were considered very glaring, but there is a trend that streets where the lighting is considered dark, uneven, limited in area and poorly matched to the site were also considered not glaring. Basically, this is a reflection of the fact that it is difficult to have a glaring lighting installation when you have very little light. As for comfort, the comfortable/uncomfortable scale showed good agreement with all the other scales except glaring/not glaring suggesting that the observers tended to interpret this as meaning how at ease/uneasy they felt rather than any degree of visual discomfort. Such post hoc rationalizations are the penalty of ambiguity.

While the results shown in Figure 11.14 suggest that the levels of glare produced by current lighting practice in the United States are not a major determinant of whether the lighting of a street is considered good or bad, this may not be the case elsewhere. Glare is always a possibility and needs to be considered when designing any lighting for pedestrians. One way to do this would be to apply the discomfort glare prediction system designed for drivers facing an opposing vehicle's headlamps (Schmidt-Clausen and Bindels, 1974, see Section 10.2.5), but this is not easy in practice because it contains a term for adaptation luminance which is difficult to define outside the laboratory. Also, when the glare source is viewed directly, this system predicts an infinitely high level of discomfort glare. Bullough et al. (2008) have produced an alternative model for predicting discomfort glare for outdoor lighting based on a series of experiments in which the observer looked directly at the glare source. This model uses three illuminances received at the observer's eye from different

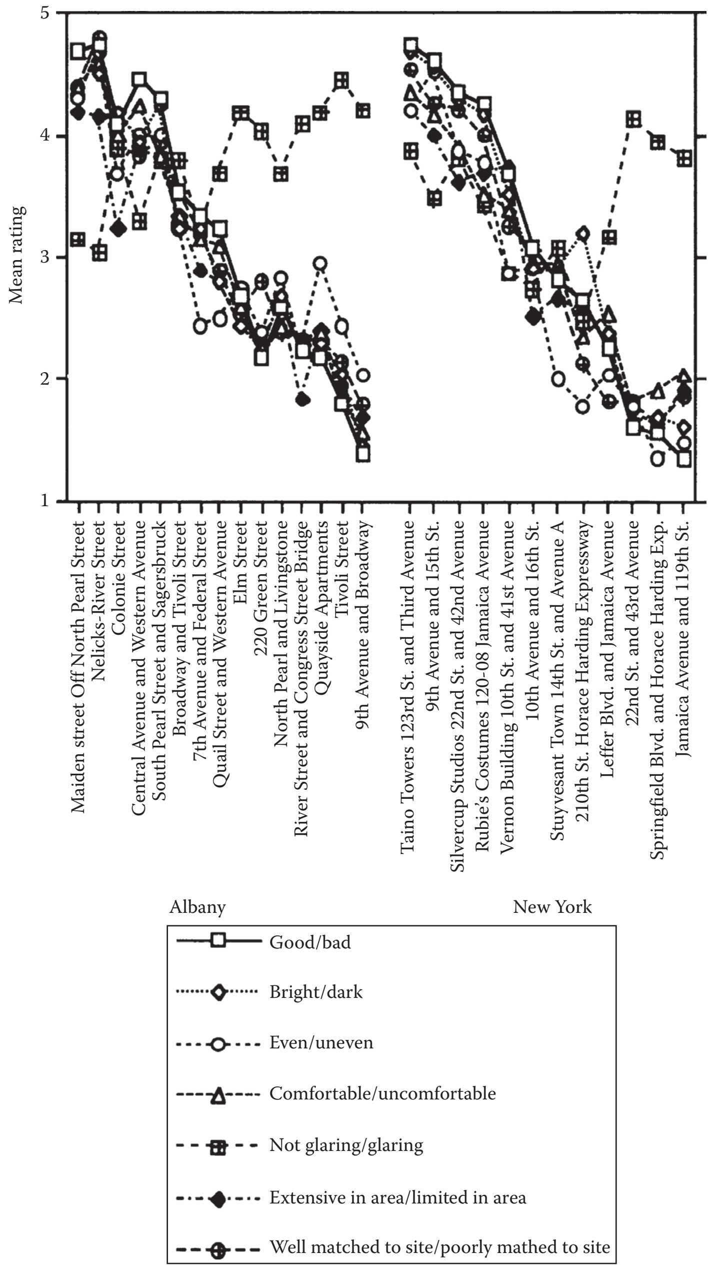


FIGURE 11.14 Mean ratings on seven 5-point scales for the lighting of 12 streets in New York City and 15 in Albany, NY. The scales are arranged so that a rating of 5 indicates the lighting is perceived as good, bright, even, comfortable, not glaring, extensive in area and well matched to site. A rating of 1 indicated that the lighting was perceived as bad, dark, uneven, uncomfortable, glaring, limited in area and poorly matched to the site. (After Boyce, P.R. et al., *Lighting Res. Technol.*, 32, 79, 2000b.)

parts of the visual environment. The three illuminances are the illuminance received directly from the glare source, the illuminance received when the glare source is turned off and the total illuminance received when the glare source is lit. The first of these illuminances is taken as the glare source illuminance (E_L), the second is taken as the ambient illuminance (E_A) and the difference between the third and the sum of the first and second illuminances is taken as the surround illuminance (E_S). The model takes the following form:

$$DG = \log(E_L + E_S) + 0.6\log\left(\frac{E_L}{E_S}\right) - 0.5\log E_A$$

where DG is a measure of discomfort glare. The quantity DG can be converted to values on the de Boer scale using the following equation:

$$W = 6.6 - 6.41\log(DG)$$

where W is the glare rating on the de Boer scale. The de Boer scale is a nine-point glare scale with five anchor points labelled 1 = unbearable, 3 = disturbing, 5 = just admissible, 7 = acceptable and 9 = unnoticeable. Note that on this scale, lower values are more uncomfortable. Conditions producing ratings of 4 or less are usually considered uncomfortable.

Figure 11.15 shows the mean ratings on the de Boer scale given by the observers in all the experiments conducted by Bullough et al. (2008) plotted against the model predictions for the same conditions. Clearly the model is not perfect but it does show a reasonable correlation coefficient between measured and predicted glare ratings ($r = 0.77$). Later work confirmed that this equation is suitable for glare sources subtending less than 0.3°, but for larger sources, Bullough and Sweater-Hickcox

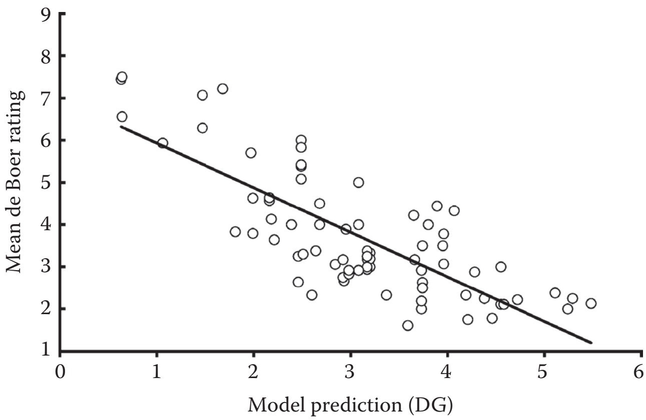


FIGURE 11.15 Mean ratings of discomfort glare on the de Boer scale plotted against the predicted de Boer ratings made by the Bullough et al. (2008) model for outdoor lighting. (After Bullough, J.D. et al., *Lighting Res. Technol.*, 40, 225, 2008.)

(2012) suggest a different conversion equation to take the effect of maximum glare source luminance into account, namely,

$$W = 6.6\log(\mathrm{DG}) + 1.4\log\frac{50{,}000}{L_s}$$

where

W is the glare rating on the de Boer scale
DG is the measure of discomfort glare derived from the previous equation
L_s is the maximum luminance of the glare source (cd/m^2)

Regardless of which conversion equation is used, this approach does have one great advantage for practical application. Given that only illuminances are required to make a prediction, it is easy to implement in existing lighting design software.

Controlling glare is necessary to limit visual discomfort but can do little to generate an attractive luminous environment. One attempt to examine what is required to do this was made by Rea et al. (2009a) who asked people observing an isolated road lit by two different light sources giving similar light distributions to imagine that they were sitting in a street café and asked which lighting would they consider more acceptable to socialize and chat. The answers given were very mixed, with no clear preference for the different illuminances (5–15 lx) or light sources (MH and HPS). Possibly, the lighting examined, which was intended for conventional road lighting, and the site were so far from what is normally associated with a street cafe that the people were confused. Certainly, their comments suggest that a warm lighting effect is desirable in which case CCT of the light source is also important.

This should not be taken to mean that brightness and colour rendering can be ignored. Fotios and Cheal (2011c) used a pair of side-by-side booths to compare all possible pairs of five light sources. The five light sources were two forms of MH, an HPS, a compact fluorescent and a two-peak LED. For each pair of light sources, the observer was asked to say under which light source was the appearance of the skin of the hands preferred, under which light source was the appearance of a 24-colour test chart preferred and under which light source was the appearance of the booth preferred. These preference judgments were made at equal horizontal illuminance in the booths (5 lx) and at equal spatial brightness, that is, with different illuminances in the two booths but set by the observers to equal brightness. Analysis of these preferences showed that for equal illuminance, one form of MH was the most preferred for skin, colour chart and the whole booth and HPS was the least preferred; the other light sources were intermediate between these extremes. For equal spatial brightness, the same MH light source was again the most preferred for skin, colour chart and the whole booth, but the least preferred was the compact fluorescent for skin, the HPS for the colour chart and the two-peak LED for the whole booth. Combining the preferences for each light source for all three stimuli and plotting them against a number of light source spectrum metrics, that is, CIE general CRI, CCT, gamut area index, scotopic/photopic ratio and the CIE mesopic system (see Section 1.6), revealed that the CIE general CRI was most closely related to the preferred appearance.

It can be concluded that when it comes to creating lighting that is visually comfortable and attractive, meeting simple recommendations of horizontal illuminance is not enough. Attention has to be paid to the CCT, colour rendering and scotopic/photopic ratio of the light source used. Further, the luminaires have to be chosen and positioned so as to avoid disability and discomfort glare and to provide a light distribution that is even enough to be safe but diverse enough to be interesting. There is still some way to go before lighting recommendations for pedestrians can approach this ideal.

11.7 COMPLETING THE PICTURE

From the previous discussion, it should be clear that the identification of the lighting conditions required by pedestrians is far from complete. Indeed, research in this area to date has been rather like trying to complete a jigsaw without knowing what the picture is and with some pieces missing. We have an outline of what the picture should be in that we know what it is that pedestrians want to be able to see in general but not in particular. This lack of detail is exacerbated by the fact that different priorities will be given to different desires in different areas. So, for a typical residential street, priority will be given to safe movement; in a park, priority will be given to security and the appearance of the space; and in a commercial pedestrianized area, safe movement, security and appearance will all be important. Unfortunately, what lighting conditions are required to meet these three objectives are not equally well understood.

The ability to move safely along and across a road has been systematically examined. The results are readily understandable in that this is essentially a matter of visual performance and the distance over which the performance has to be achieved is limited. The effects of illuminance and light spectrum can be predicted given that the visual size, luminance contrast and colour difference of obstacles can be identified. As a general rule, the higher the illuminance and the higher the scotopic/photopic ratio of the light spectrum, the better will be the on- and off-axis detection of obstacles.

The situation for security is not so well understood. This is because the perception of security is a psychological phenomenon and people will differ over how they interpret the environment around them. Some who are confident about being outside at night may not bother about seeing at a distance, while those who are nervous might want to see a long way ahead. This means that light distribution is likely to be important for ensuring security: the more uniform the lighting, the greater the ability to see far ahead. One factor that has been established to be important for a feeling of security is spatial brightness. The effects of illuminance and light spectrum on spatial brightness are well understood; again, a higher illuminance and a light source with a greater scotopic/photopic ratio will produce a greater perception of spatial brightness. What is not well understood is how significant the lighting of the area around the route is. Feeling secure on the street or in a park requires being able to see all around, not just ahead. Of course, sometimes where one can see is constrained by surrounding buildings, but where this is not the case, consideration should be given to areas adjacent to the path.

The situation is even more vague for ensuring comfort and beauty. Lighting recommendations deal with physical discomfort by restricting glare from luminaires, but that is about all. There is nothing to guide the designer in creating an attractive and beautiful scene, and given the limited range of lighting metrics available, for example, illuminance, illuminance uniformity, scotopic/photopic ratio and glare index and the distances over which aspects of the environment can affect perceptions of beauty, it seems unlikely that there ever will be. Given this situation, it would be better to concentrate research on light distribution. This is one variable that is believed to be important for feelings of security that could be implemented in recommendations but has not so far been investigated. This is because, in the past, it was difficult to study the effect of light distributions because of the large-scale logistics involved in manipulating light distributions in the field. Today, that may not be necessary. Software is available that can produce photometrically accurate simulations of outdoor lighting (Rea et al., 2010b), and there are means to present the image on a wide screen. If driving simulators can be produced, why not walking simulators? The use of such technology would enable a systematic study of light distribution and perceptions of security, a study that could lead to more well-founded recommendations for lighting for pedestrians.

11.8 SUMMARY

Lighting for pedestrian use at night is provided on residential roads, in car parks, in pedestrianized areas and in public parks. This lighting can take various forms from conventional road lighting through area floodlighting to landscape lighting. At a basic level, what pedestrians want from such lighting is to be able to see where they are, to be able to move safely over the ground, to assess the risk to personal security and to avoid visual discomfort. At a more advanced level, people also recognize that there is a positive side to lighting. Depending on how it is done, lighting useful for pedestrians can be a thing of beauty. Even if it is not, depending on the features of the environment available, lighting of buildings, parks, fountains, etc., can contribute to an exciting and attractive night-time environment.

There are various national recommendations made for the lighting of areas where pedestrians are to be found. These recommendations use average horizontal illuminance on the pavement as a criterion but differ markedly in the range of values chosen, from Australia with a range of 0.5–7 lx, the United States with a range of 3–9 lx and European Union countries with a range of 2–15 lx. Some countries make an adjustment in the recommendations depending on the light spectrum of the light source used. It is important to note that these recommendations are minima. Many applications, such as shopping malls, use much higher levels.

It might be thought, justifiably, that simple horizontal illuminance recommendations will not go far towards ensuring an attractive night-time environment but they are relevant to avoiding injury through tripping and falling. A study of the speed and manner of movement through a large open-plan office under different illuminances showed that an average illuminance of 1 lx on the route was required for smooth and steady movement. Others have shown that a significantly raised paving stone edge can be detected on 95% of occasions under illuminances ranging from 0.10 to 0.62 lx depending on the distance ahead a person is looking. Such average illuminances are of the same order as the lowest illuminances recommended for residential roads in Australia and somewhat less than those used in the United Kingdom or the United States.

Anyone walking down the street is likely at some point to have to cross the road. Pedestrians who do not use recognized crossing points are at much greater risk of death or injury than those who do. Lighting is sometimes used to emphasize the presence of a pedestrian crossing and to increase the visibility of a pedestrian on the crossing. Recommendations exist in different countries for the lighting of pedestrian crossings, but they consist of little more than horizontal or vertical illuminances. A more comprehensive approach is needed that assesses the effect of lighting on the stimulus a pedestrian using the crossing presents to the visual system of an approaching driver, particularly the luminance contrast.

Another concern for pedestrians is their security. Lighting has a role to play in making people feel safe outside at night. That role is to make the surrounding scene visible. By making the surroundings visible, lighting can increase the distance at which a threat can be detected and increase the time available in which to frame an appropriate response. Two approaches have been taken to determining what form of lighting should be used to ensure a perception of safety. One has concerned the perception of spatial brightness, a bright scene being considered safer than a dark scene. There are three aspects of a lighting installation that are likely to affect the perception of spatial brightness: the level and distribution of illuminances and the light spectrum. Of these, only two aspects have been extensively studied: illuminance and light spectrum. Studies of car parks in urban and suburban areas have examined the effect of illuminance and concluded that an illuminance in the range of 10–30 lx is necessary. Both laboratory and field studies have been used to explore the effects of light spectrum. Their results indicate the spatial brightness is increased by using higher illuminances and a light source with a high scotopic/photopic ratio.

The other approach to identifying the lighting conditions suitable for pedestrian security has been to determine what level of visual performance can be achieved under different illuminances and light spectra. A number of different tasks have been used ranging from simple visual functions to real tasks. Visual acuity shows a clear effect of illuminance but not light spectrum. Off-axis detection can be improved by increasing illuminance or using a high-scotopic/photopic-ratio light source. Among the more realistic tasks used is facial identification. Illuminance on the face is important for increasing the distance at which a person can be recognized, but the results for light spectrum are inconsistent. This inconsistency may occur because there is some other factor that is more important than light spectrum. Light distribution seems an obvious possibility as it will change the pattern of light and shade on the face. However, there is an argument that facial recognition may not be important for pedestrian security and that what is required is the ability to recognize intent in anyone approaching. How well this can be done under different lighting conditions has not yet been systematically studied.

Pedestrians using the streets at night want to feel comfortable, but what this means can be ambiguous, some people taking it to mean feeling at ease, while others taking it to refer to a perception of visual discomfort. One study in which a number of different scales were used to describe the lighting of city streets showed that good lighting is perceived to be bright, even, extensive in area and well matched to the site suggesting that the levels of glare produced by current lighting equipment and practice are not important. Much more important is the amount and distribution of light.

From the previous discussion, it should be clear that the attempt to identify the lighting conditions required by pedestrians is far from complete. The ability to move safely along and across a road has been systematically examined. The results are readily understandable in that this is essentially a matter of visual performance and the distance over which the performance has to be achieved is limited. The situation for pedestrian security is not so well understood. This is because the perception of security is a psychological phenomenon and people will differ over how they interpret the environment around them. Some who are confident about being outside at night may not bother about seeing at a distance, while those who are nervous might want to be able to see well all around. This means that light distribution is likely to be important for ensuring security.

The situation is even more vague for ensuring comfort and beauty. Lighting recommendations deal with physical discomfort by restricting glare from luminaires, but that is about all. There is nothing to guide the designer in creating an attractive and beautiful scene, and given the limited range of lighting metrics available and the distances over which aspects of the environment can affect perceptions of beauty, it seems unlikely that there ever will be. Given this situation, it would be better to concentrate research efforts on light distribution. This is one variable that is believed to be important for feelings of security that could be implemented in recommendations but has not so far been investigated. In the past, it was difficult to study the effect of light distributions because of the large-scale logistics involved in manipulating light distributions in the field. Today, that may not be necessary. Software is available that can produce photometrically accurate simulations of outdoor lighting, and there are means to present the image on a wide screen. The use of such technology would enable a systematic study of light distribution and perceptions of security, a study that could lead to more well-founded recommendations for lighting for pedestrians.

12 Lighting and Crime

12.1 INTRODUCTION

Crime began with Adam and Eve and has been with us ever since. Crime can take many different forms, some major, some petty; some against people and some against property. The consequences of crime for the victim can range from the irritating to the fatal. The consequences for society can also be dramatic, changing the ways in which people perceive each other and how they behave towards each other. But crime is not always a negative for society. Every so often in human history, what at the time was called widespread criminal activity has lead to advances in human rights and tolerance. Indeed, many nations owe their existence to such activity. This chapter is devoted to the role of lighting as a means of preventing and detecting criminal activity, regardless of whether that activity is later considered to be justified or not.

12.2 SOME HISTORY

Attempts to use lighting as a measure to combat crime on the streets have been made since the fifteenth century (Painter, 1999, 2000). In 1415, all owners of property in London rated at £10/year or more were ordered to hang out a luminaire each winter evening between All Hallows (1 November) and Candlemas (2 February), except on the nights from 7 days before the full moon to 7 days after the full moon, when moonlight was considered to be sufficient. To fill in the gaps between this inevitably sparse provision, citizens who had to go out at night relied on linkmen, men and boys who carried flaming torches and escorted their clients through the darkened city. This combination of lighting provided by individual householders and the use of linkmen persisted until the eighteenth century, despite complaints about its inadequacy and the widespread belief that the linkmen where often hand in glove with what are now called muggers (Brox, 2010).

Paris followed a similar route to London but more rapidly developed a public lighting system. In the fifteenth century, it was decreed 'during the months of November, December, and January, a luminaire is to be hung out under the level of the first floor window sills before 6 o'clock every night. It is to be placed in such a prominent position that the street receives sufficient light' (Schivelbusch, 1988). In 1667, the authorities in France decided to suspend luminaires on cables over the centre of the streets rather than mount them on houses and thereby to create a public lighting system under the control of the police. This link between lighting and the police had the consequence of associating street lighting with the maintenance of public order under an absolutist monarchy and hence as an instrument of repression rather than as a friend of the citizen. The result was an enthusiasm for luminaire smashing at times of political unrest (Brox, 2010).

As cities grew and the concepts associated with the social contract between the governing and the governed developed, there was increased demand for some form of public lighting at night. This demand was first widely met by the introduction of gas lighting, the gas being delivered to each luminaire through a distribution system from a central source. In London, by 1823, the gas lighting system had grown to such an extent that 39,000 gas lamps provided lighting for 215 miles of road (Chandler, 1949). Gas lighting rapidly spread to other cities in Europe, although not without resistance. In Cologne, many citizens were early dark sky enthusiasts and asserted that God had ordained that certain hours of darkness should prevail and that any attempt to illuminate the streets at night was an encroachment on the divinely established order of the universe (Roberts, 1997). Despite this fundamentalist view, public lighting powered by gas continued to spread until virtually every major city had such provision. Gas was the major source for exterior lighting at night for about 100 years, although the first exterior electrical lighting installations, using arc lamps, were installed in the 1850s. The brightness of these light sources was believed to be of great benefit in the fight against crime. Indeed, the police chief of New York was quoted as saying 'Every electric light erected means a policeman removed' (O'Dea, 1958). But arc lighting required continuous maintenance and so was never widely used, although Detroit had a system based on 50 m high towers that was used to light 54 km^2 of the city at the end of the nineteenth century. After 30 years, this system was dismantled, the criticism being that it provided a twilight glow over the whole area – but no effective lighting anywhere (Schivelbusch, 1988). It was not until the introduction of the incandescent lamp and the associated electrical distribution systems that gas gave way to electricity as the primary mean of providing light at night. Since then, the primary electrical light sources used for exterior lighting have changed from incandescent, through a range of discharge sources such as low-pressure sodium (LPS), mercury vapour and tubular fluorescent, to today's most widely used light sources, high-pressure sodium (HPS) and metal halide (MH), with light-emitting diodes (LEDs) rapidly increasing in number.

12.3 LIGHTING AS A CRIME PREVENTION MEASURE

Once widespread provision of exterior lighting at night had been accomplished, interest in the question of its effects on crime diminished, and attention switched to the most appropriate form of exterior lighting for driving. Interest in lighting's potential to affect crime resurfaced in the United States in the 1960s, coincident with a dramatic rise in the incidence of crime. Municipalities across America improved their street lighting to combat crime and some encouraging results were reported (Wright et al., 1974). However, in 1979, Tien et al. (1979) published an extensive review of the impact of lighting projects on crime in the United States. Inclusion in the review was restricted to street lighting projects that had been installed with an effect on crime in mind and that were not clearly highway lighting. This latter criterion was adopted because it was assumed that road lighting was primarily concerned with vehicle safety and not pedestrian security. Applying these two criteria led to a total of 103 street lighting projects that had been implemented in the United States, from 1953 to 1977. Two other criteria were then applied; projects were only considered further if they took place in cities with a population of at least 25,000 and after 1970. The population limit was adopted because of the desire to compare like situations. The date requirement was adopted because of the difficulty in recovering or collecting data from long completed projects. Applying these two criteria reduced the project pool to 45. Finally, a fifth criterion was applied; a project had to have some data available on the lighting installation used, people's attitudes or behaviour and the incidence of crime. The outcome was a set of 15 street lighting projects for detailed evaluation.

The detailed study revealed a pattern of partial information, inadequate or inappropriate measurements, limited control of relevant variables and invalid statistical analyses, where any statistical analysis had been applied at all. The conclusion reached by Tien et al. (1979) was that there was no statistically significant evidence that improved street lighting influenced the level of street crime. However, there was some indication that improved street lighting decreased the fear of crime.

Other studies of specific street lighting projects and specific types of crime conducted at the same time have confirmed the difficulty in obtaining unambiguous evidence of the effect of street lighting on street crime. In one case (Griswold, 1984), the influence of the improved lighting could not be disentangled from the effects of security surveys carried out at the same time. In two other studies (Krause, 1977; Lewis and Sullivan, 1979), the apparent reduction in crime against property following an improvement in street lighting could be seen as part of a continuing trend that started before the lighting was changed.

The effect of the Tien et al. (1979) review was to dampen enthusiasm for lighting as a means to combat crime for about a decade. Then, Painter (1988) reopened the question. She identified three aspects of the studies reviewed by Tien et al. (1979) that might be expected to limit their sensitivity. The first was the fact that virtually all the studies involved large areas. Large areas lead to averaging, which makes it very difficult to isolate the impact of lighting from that of all the other factors which may affect the level and type of crime and the fear of crime. The second was the use of police crime statistics. Crime statistics, as conventionally collected, are coarse measures that group together a wide range of offences. Further, not all crimes are reported to the police. This makes it difficult to know if improved street lighting generates a change in the level or the pattern of crime. The third was that there had been no examination of the effects of different types of lighting on the incidence of various types of crime. Different lighting installations are likely to have different impacts on different types of crime, so to group them together risks masking any effects.

Painter's response to this analysis was to conduct a field experiment in an outer area of London (Painter, 1988). The project focused on the effect of lighting on particular crimes in a very localized area. Specifically, the area examined was one street and a tunnel under a railway. The street was heavily used because it served as a pedestrian route from a residential area to commercial, transport and leisure facilities. The types of crime examined were those representative of common street crimes: violence against the person (robbery, theft and physical and sexual assault), vehicle crime (theft and damage) and incidents of harassment. The study was conducted as a before and after design. The street lighting before gave illuminances on the street in the range 0.6–4.5 lx from LPS luminaires, while the street lighting after gave illuminances in the range 6–25 lx on the street from HPS luminaires. Data were collected by a street survey carried out after dark. The information sought from people using the street was their experience of crime in the area, their fear of crime in the area and any physical precautions they took. The interviewers carrying out the survey also recorded any crime and/or harassment they observed or experienced. Table 12.1 lists the number of crime incidents the 207 respondents had experienced on the street over a 6-week period before the lighting was changed and the number of crime incidents another 153 respondents had experienced on the street during the 6 weeks immediately after the change in lighting. Table 12.2 lists the percentage of respondents identifying the change in lighting conditions and, if they did, the nature of the change they had observed. It also gives the respondents' change in fear of crime following the change in lighting. In this study, at least, there is some evidence that improving street lighting by increasing illuminance and using a better colour-rendering light source does reduce the incidence of some types of crime and people's fear of crime.

Obviously, this study, with its limited area examined and brief time of exposure, cannot be said to prove conclusively that improved street lighting reduces the incidence of crime. Nonetheless, after the ambiguities of the macroscale studies described by Tien et al. (1979), the results of this microscale study by Painter (1988) are at least clear. These findings lead to an outburst of similar studies in the United Kingdom, some done by Painter herself (Painter, 1989, 1991a, 1994, 1996), some done by others (Barr and Lawes, 1991; Burden and Murphy, 1991; Davidson and Goodey, 1991; Glasgow Crime Survey Team, 1991; Herbert and Moore, 1991; Nair et al., 1993; Ditton and Nair, 1994; Shaftoe, 1994; Cridland, 1995).

TABLE 12.1
Crime Experienced on the Street by Respondents over 6-Week Periods before and after the Change in Lighting

	Number of Respondents Experiencing	
Type of Crime	**Before Lighting Change (n = 207)**	**After Lighting Change (n = 153)**
Robbery	2	0
Sexual assault	1	0
Physical assault	2	1
Threats	4	0
Stolen automobile	4	1
Stolen motorcycle	4	0
Stolen bicycle	1	0
Automobile damage	2	1
Motorcycle damage	2	0
Total	22	3

Source: After Painter, K., *Lighting and Crime Prevention: The Edmonton Project*, Middlesex Polytechnic, Hatfield, U.K., 1988.

TABLE 12.2
Changes in Perceptions of 153 Respondents Following the Change in Lighting

Question	Percent Answering Positively		
	All	Men	Women
Noticed the change in the lighting of this street?	69	63	82
If you noticed the change in lighting, in what way is the lighting different?			
Lighting brighter.	99	—	—
Lighting makes it easier to recognize people.	97	—	—
Lighting improved.	96	—	—
Lighting better maintained.	82	—	—
Lighting casts less shadows.	65	—	—
Lighting more attractive.	58	—	—
Lighting improved look of area.	47	—	—
During the past six weeks, while walking on this road, would you say that your feelings of personal safety have:			
Increased.	62	61	63
Decreased.	3	4	2
Remained the same.	31	29	33
Do not know.	4	5	2

Source: After Painter, K., *Lighting and Crime Prevention: The Edmonton Project*, Middlesex Polytechnic, Hatfield, U.K., 1988.

The results were mixed. Nearly all these studies showed a reduction in fear of crime following improved street lighting, particularly for women and the elderly (Painter, 1991b). However, while most of the studies showed a reduction in the incidence of crime following improvements to the street lighting, others found no effect, while yet others found an increase in some types of crime (Painter, 1996). Further, at least one follow-up study found that the marked reduction in level of crime that immediately followed the improvement in street lighting was not sustained over time (Nair and Ditton, 1994). Obviously, there is no simple link between lighting conditions and the prevalence of crime. A study conducted in Ashton-under-Lyne, in northwest England, will serve as an example of the variability of the effect of improving street lighting (Painter, 1991a). This study took place on a public housing estate consisting of three tower blocks surrounded by maisonettes and examined the incidence of crime over a period of 12 months. Table 12.3 shows the incidence of different types of crime before and after the estate lighting was improved, as reported by the households on the estate. It should be noted that these data indicate a much higher level of crime than was recorded in police statistics, both before and after the lighting was improved. Nonetheless, there is again evidence that, overall, the incidence of crime has been reduced following the improvement in the lighting, although

TABLE 12.3
Crime Experienced by Households on the Estate before and after the Lighting Was Improved

	Number of Respondents Experiencing	
Type of Crime	**Before Lighting Change ($n = 197$)**	**After Lighting Change ($n = 197$)**
Burglary with loss	46	25
Attempted burglary	53	51
Outside household theft	35	10
Theft from person	6	1
Street robbery	15	3
Public physical assault	9	19
Vandalism/home	25	27
Vehicle stolen	5	5
Theft from vehicles	5	15
Vandalism/vehicle	25	13
Pestered/insulted	81	64
Sexual assault/rape (women only)	2	0
Sexual harassment (women only)	42	35
Total	349	268

Source: After Painter, K., *Lighting J.*, 56, 228, 1991a.

some types of crime such as theft from vehicles and physical assault have increased. As for fear of crime, the improvements in the lighting produced a 41% reduction in those who felt unsafe on the estate after dark and lesser reductions in the number afraid of being robbed (25% reduction), afraid of vandalism (14% reduction) and afraid of sexual assault (10% reduction).

While this work was being done, another study covering a large urban area was undertaken in which the street lighting of the whole of Wandsworth, a borough of London, was improved. The level of crime reported to the police was monitored for 12 months before and after the lighting was changed (Atkins et al., 1991). The conclusion of the authors of this study was that there was no effect of improved street lighting on the incidence of crime. However, a later review of this study (Pease, 1999) came to a different conclusion, pointing out that there was a 15% reduction in the level of crime following the improvement of the lighting, although the reduction occurred both day and night, 11% by day and 17% by night. The reason for the different interpretations of the data collected in Wandsworth lies in the question, can street lighting that only operates at night have an impact on crime during the day? If it is assumed that street lighting can only have an effect at night, then the interpretation of the original authors is correct, but if street lighting can affect crime during the day, then the conclusion of the revisionists is correct. Possible answers to this question will be discussed in Section 12.4.

While argument was raging over the Atkins et al. (1991) study, more data were accumulating. Probably the most sophisticated study is that undertaken in Stoke-on-Trent in the North Midlands of England (Painter and Farrington, 1999). Three areas of housing were identified, each with a stable population. One area was designated as the experimental area, the second as an adjacent area and the third as a separate control area. Before the street lighting in the experimental area was improved, interviews were conducted with households in all three areas about their experience of crime in the last 12 months, their perceptions of the area and their behaviour. Then, the lighting of the experimental area was improved from widely spaced incandescent lighting on roads, and unlit footpaths, to more closely spaced HPS lighting on both roads and footpaths. The lighting of the adjacent and control areas was unchanged. Twelve months after the lighting in the experimental area was improved, as many of the same households as were available in the three areas were again interviewed about their experience of crime in the preceding 12 months and about their perceptions and behaviour. The experimental area was intended to directly measure the effect of lighting. The control area was intended to provide a baseline against which any changes in the level of crime in the city could be monitored. The adjacent area was intended to explore the possibility of diffusion occurring. In the case of lighting, this means that the provision of improved lighting in one area will lead to similar benefits for crime reduction in adjacent areas. Diffusion has been found to occur in relation to other crime prevention measures. For example, the installation of a closed-circuit television (CCTV) system aimed at reducing thefts of cars from a university car park also produced a reduction in theft of vehicles from an adjacent car park not covered by the cameras (Poyner, 1991). Diffusion is the opposite of another possible effect of taking crime prevention measures in a given area, namely, the displacement of the crime to other areas. Displacement, too, has been found following the introduction of crime prevention measures (Gabor, 1990) although it is by no means inevitable (Clarke, 1995), presumably because a certain amount of crime is opportunistic rather than systematic in nature.

Table 12.4 shows the incidence of crime, expressed as the percentage of households in the three areas that had been the victims of crime in the 12 months before and after the relighting of the experimental area. Crime was divided into four categories: burglary, including attempts; theft from outside the home, vandalism of the home or bicycle theft; theft of or from vehicles or damage to vehicles; and personal crime against any member of the household, including street robbery, snatch theft, assault, threatening behaviour and sexual pestering of females. An examination of Table 12.4 shows marked reductions in the prevalence of crime in three of the four crime categories in the experimental area and no statistically significant changes in the adjacent and control areas for any crime category, following the improvement of the lighting in the experimental area.

Measuring the incidence of crime as the percentage of households experiencing a particular type of crime has the limitation that a household may experience the same type of crime more than once. Table 12.5 shows the incidence of crime, expressed as the average number of crimes of each category experienced per 100 households, in the three areas, following the improvement of the lighting in the experimental area. Again, there is a statistically significant reduction in two categories of crime in the

TABLE 12.4
Percentage of Households Experiencing Different Categories of Crime in Three Areas, before and after the Lighting Was Improved in the Experimental Area

	Experimental Area		Adjacent Area		Control Area	
Crime Category	**Before (*n* = 317) (%)**	**After (*n* = 278) (%)**	**Before (*n* = 135) (%)**	**After (*n* = 121) (%)**	**Before (*n* = 88) (%)**	**After (*n* = 81) (%)**
Burglary	24	21	20	18	13	16
Outside theft/ vandalism	*21*	*12*	30	22	17	16
Vehicle crime	*26*	*16*	19	12	11	9
Personal crime	*13*	*6*	16	11	7	5

Source: After Painter, K. and Farrington, D.P., Street lighting and crime: Diffusion of benefits in the Stoke-on-Trent project, in K. Painter and N. Tilley (eds.), *Crime Prevention Studies*, Criminal Justice Press, Monsey, NY, 1999.

Note: Percentages printed in italics represent the differences that are statistically significant ($p < 0.05$).

TABLE 12.5
Average Number of Victimizations per 100 Households for Four Different Categories of Crime in Three Areas, before and after the Lighting Was Improved in the Experimental Area

	Experimental Area		Adjacent Area		Control Area	
Crime Category	**Before (*n* = 317)**	**After (*n* = 278)**	**Before (*n* = 135)**	**After (*n* = 121)**	**Before (*n* = 88)**	**After (*n* = 81)**
Burglary	38.5	32.7	31.1	24.8	15.9	16.0
Outside theft/ vandalism	43.8	27.0	65.2	38.8	26.1	34.6
Vehicle crime	*47.6*	*25.5*	*34.8*	*18.2*	17.0	11.1
Personal crime	*43.8*	*14.0*	*48.9*	*16.5*	10.2	6.2

Source: After Painter, K. and Farrington, D.P., Street lighting and crime: Diffusion of benefits in the Stoke-on-Trent project, in K. Painter and N. Tilley (eds.), *Crime Prevention Studies*, Criminal Justice Press, Monsey, NY, 1999.

Note: Percentages printed in italics represent the differences that are statistically significant ($p < 0.05$).

experimental area following the improvement of the lighting. Interestingly, for this measure, there are statistically significant reductions in the same crime categories for the adjacent area as well, suggesting that diffusion has occurred. There are no statistically significant changes in this measure for the control area following the improvement of the lighting in the experimental area.

As for perceptions, there were statistically significant increases in the number of households in the experimental area who considered their estate well kept

(39%–57%) after the improvement in the lighting and that their quality of life had improved in the last year (4%–23%). The improved lighting was certainly noted, only 4% of households saying the estate was badly lit after the lighting was improved (74% before). As for behaviour, counting of the number of pedestrians on the streets after dark revealed a 70% increase in males in the experimental area, compared with 29% and 25% increases in the adjacent and control areas, respectively. For females, there was a 70% increase in the experimental area and 42% and 41% increase in the adjacent and control areas, respectively. Clearly, improving the lighting by increasing the illuminance has lead to a greater use of the streets at night, even though the colour rendering of the new lighting is worse.

About the same time as the Stoke-on-Trent study, Painter and Farrington (1997) completed a similar study in Dudley, in the West Midlands of England. In this study, the lighting of a local authority housing estate was improved while the lighting of a comparable, nearby estate was not. What makes this study interesting is that details of the level of crime on the two estates, before and after improving the lighting of one, were obtained from two different sources. One source was similar to that used in Stoke-on-Trent, namely, the adult residents of the two estates. Interviews with these adults revealed that following the lighting improvements, they experienced less crime on the estate with improved lighting (a 23% decrease) but not on the control estate, where the lighting was unchanged (a 3% decrease). The second source was self-reported delinquency data collected from young people in the age range 12–17 years and living on the two estates (Painter and Farrington, 2001a). These data showed that the admitted level of delinquency decreased more on the relit estate than on the control estate after the lighting was improved.

Following all this effort, Farrington and Welsh (2002) carried out a systematic review of the literature on the use of lighting for crime prevention. Studies were included in the review if lighting was the main change and the incidence of crime was the outcome measure, if there were both experimental and control areas and if there were before and after measures of crime and the total number of crimes in each area before the change was at least 20. In total, eight older American studies and five more recent British studies were admitted to the review. The conclusion was that for all 13 studies, taken together and on average, improved lighting reduced crime in the experimental area by 20% relative to the control area.

This conclusion has been challenged on two statistical grounds (Marchant, 2004). One is that the data used in the review suffer from an underestimation of the variability in the incidence of crime so that what seem to be statistically significant differences are really not statistically significant. The other is that the studies suffer from regression to the mean (Bland and Altman, 1994). The idea here is that the experimental area chosen for improved lighting will normally be more crime-ridden than the control area. Consequently, crimes are likely to decrease more in the experimental area than in the control area simply because of the normal fluctuations in the incidence in crime. Marchant (2004) concludes that any claim that brighter lighting reduces crime is unfounded. Naturally enough, Farrington and Welsh (2004) disagree and claim that their conclusion still holds even if the variance is greatly increased. Farrington and Welsh (2006) specifically addressed the regression to the mean argument by examining recorded crime rates in police command units in England and Wales and conclude that regression to the mean may cause a 4% decrease in crimes but that is not enough to account for much of the larger decrease produced by improved street lighting.

No doubt this argument will continue for many years (Welsh and Farrington, 2008; Marchant, 2011), but the keywords to note about the magnitude of the effect of improved lighting on crime reduction are on average. An average is a measure of central tendency for a distribution and is always associated with a spread of values. This means some of the effects of improved lighting will be greater than the average and some less. This may explain why some studies find that improved lighting produces a decrease in crime, others find no effect and some find an increase in crime. An average may be what is needed for determining government policy but it is of limited use to anyone who has to decide what to do about reducing crime in a specific area, particularly as what constitutes improved lighting in the studies considered is often poorly defined.

Two specific studies not included in the review demonstrate the dangers of making simple, sweeping statements about lighting as a crime prevention measure. The first is the Chicago alley lighting project (Morrow and Hutton, 2000). In this, the lighting of alleys in two very deprived and depraved areas of Chicago was increased by changing the luminaires so that the wattage of the light sources used could be increased from 90 to 250 W, thereby dramatically increasing the illuminance. Unfortunately, the outcome of these changes was that crime increased in both areas after the brighter lighting was installed, principally due to increased substance abuse violations. The second is the work of Loomis et al. (2002). They carried out a thorough epidemiological case-control study of the impact of various safety measures on the incidence of workplace homicide in North Carolina. One hundred and five workplaces, where a worker had been murdered in the years between 1994 and 1998, formed the case group. The control group was an industry-matched random sample of 210 workplaces at risk during the same period. The safety measures considered were environmental ones, such as bright lighting inside and outside, surveillance cameras and cash drop boxes, and administrative measures such as limiting public access, prescreening employees and never having staff work alone. The results showed that strong and consistent reductions in the risk of a worker being murdered at work were associated with bright exterior lighting (odds ratio = 0.5) and with not having people working alone at night (odds ratio = 0.4).

12.4 THE REASON WHY

The evidence given in the studies considered earlier leaves little doubt that lighting can play a part in crime prevention. Improving lighting can lead to a reduction in crime but it may not. There can be no guarantees. After all, if all that was necessary to prevent crime was to provide a lot of light, there would be no crime during daytime. This conclusion implies that there are circumstances in which lighting will be an effective crime countermeasure, either alone or in combination with other measures, and circumstances in which it will not. To determine what those circumstances are, it is necessary to consider the mechanisms by which lighting might impact crime.

Anderson (1981) asserts that virtually all human thought and behaviour has multiple causes, the result of many co-acting factors. There seems little reason to suppose that criminal behaviour and the fear of crime depart from Anderson's assertion. This means that lighting is only one among many factors that can influence the incidence of crime. The question then arises: Why might lighting be expected to reduce crime and the fear of crime?

The answer to this question can be framed in terms of the visibility and message routes by which lighting conditions affect human performance (see Section 4.2). Functionally, the most obvious and only certain effect better lighting can have is to change how well people can see, that is, improve visibility. It is well established that increasing the illuminance and hence the adaptation luminance increases the speed of visual processing, improves the discrimination of detail and makes colour judgments more accurate (see Section 2.4). Reducing the adaptation luminance has the reverse effects. Different light spectra provide different stimuli to the visual system that will influence its capabilities, particularly in the mesopic state (see Section 2.3.2). Different types of street lighting also produce different patterns of light distribution. If these patterns give rise to shadows and to disability glare, the ability to see may be impaired.

Given that street lighting conditions can influence how well we see, the next question to ask is why that should be expected to influence the incidence of crime and fear of crime. After all, improved street lighting enhances visibility for both the criminal and the law-abiding equally. A plausible tactical answer is that better lighting increases the distance at which something suspicious can be seen. The greater is the distance at which a threat can be detected and the finer is the discrimination of detail possible, the greater is the time available to select and act out an appropriate response. For example, it may be possible, because facial expression and body language are visible at a distance, to recognize a threatening situation while there is still time to escape. Similarly, greater visibility at a greater distance may enable people behaving in a suspicious manner to be recognized or at least described. Such observations at a distance are a benefit to the law-abiding and can be a disadvantage to the criminal.

Strategically, improving lighting can be considered as one of several different contributors to situational crime prevention. Situational crime prevention involves the modification of environments so that crime requires more effort, poses more risk and produces lower rewards (Clarke, 1995; Pease, 1997; Welsh and Farrington, 2006). Better lighting may affect the perception of risk by increasing the ease of surveillance of the street, either formally, by the police in person or through a CCTV system, or informally, by members of the community. Better lighting may increase the effort required by enabling potential victims to take action at a distance and by limiting the locations where victims can be taken by surprise. However, better lighting may also decrease the effort required and increase the rewards by making it easier for a criminal to pick out an easy, valuable target. Thus, whether better lighting will reduce the prevalence of crime will depend on the criminal's perceived risk/reward ratio for the crime, whether the lighting helps or hinders the commissioning of the crime and the likelihood that surveillance will be translated into action. Certainly, it will not eliminate crime. This is because improving street lighting is unlikely to deter the professional criminal. Weaver and Carroll (1985) took groups of experienced and novice shoplifters through retail stores and asked them to assess the opportunities. The results showed that experienced shoplifters considered conventional crime deterrents, such as store personnel and security devices, as obstacles to be overcome and were more strategic in their assessments. Novice shoplifters decided against shoplifting in the presence of any deterrent. Applying these data to street crime suggests that improved street lighting may deter the tyro street criminal but is unlikely to deter the more experienced.

So far, this discussion of how better lighting might impact crime has been concerned with the direct effect of lighting conditions on visibility. The other mechanism by which lighting might impact crime is through changes of behaviour and community confidence. Most of the studies of the impact of better street lighting have shown that improving street lighting tended to decrease peoples' fear of crime. These findings can be understood from the results of Fisher and Nasar (1992). These authors examined the fear of crime in relation to exterior site features on a college campus. Using three different approaches, they found that fear of crime was highest in areas which offered places for criminals to hide and which had a restricted view, with few avenues for flight. At night, the effect of good lighting will tend to diminish the number of places where criminals can hide, increase the distance over which people can see and, possibly, reveal opportunities for flight. Thus, good street lighting can be expected to reduce fear of crime. The behavioural consequence of this is that more people use the streets at night (Painter, 1994; Painter and Farrington, 1999). More people on the street at night increases the number of pairs of eyes and hence the amount of informal surveillance, something that criminals consider increases the risks of their activities (Bennett and Wright, 1984).

Of course, improving street lighting will only enhance visibility after dark but this should not be taken to mean that providing good street lighting only affects crime after dark. The installation of improved street lighting is a highly noticeable activity that sends the message that someone cares about the neighbourhood (Taylor and Gottfredson, 1986). Such perceptions can lead to greater community confidence, cohesion and informal social control, and these in turn tend to lead to more surveillance by residents and a greater likelihood that such surveillance will be used to support the authorities against the criminally inclined. And this will occur by day as well as at night. It is important to note that for greater community confidence, cohesion and informal social control to occur, it is necessary that the new lighting be seen as a marked improvement over what was there before and that the intention of the people providing the lighting is perceived to be to help the community and not simply to control it. It is also necessary to appreciate that the same lighting conditions may deliver different messages to different people. For the resident, the message may be that with this new lighting, I can see everything so it is safe to go out at night. For someone driving, the message may be that this must be a dangerous area or they would not need such bright lighting. The possibility of such mixed messages suggests that it is wise to identify the recipient of any message before predicting the impact of improved lighting.

To summarize, lighting does not have a direct effect on the level of crime. Rather, lighting can affect crime by two indirect mechanisms. The first is the obvious one of facilitating surveillance by people on the street after dark, by the community in general and by the authorities. If such increased surveillance is perceived by criminals as increasing the effort and risk and decreasing the reward for a criminal activity, then the level of crime is likely to be reduced. Where increased surveillance is perceived by the criminally inclined not to matter, then better lighting will not be effective. The second mechanism by which an investment in better lighting might affect the level of crime is by enhancing community confidence and hence increasing the degree of informal social control. This mechanism can be effective both day and night but is subject to many influences other than lighting. Farrington and Welsh (2002) claim that the studies in their review indicate that the second mechanism is the more important of the two.

12.5 ESSENTIAL CHARACTERISTICS OF LIGHTING

One characteristic of many of the studies described in Section 12.3 is the very skimpy level of detail given about the lighting installations, either before or after improvement. Usually, the improvement in lighting is considered adequately described by a listing of the new lighting equipment used. Typically, the improved lighting involves the use of more light sources with higher light output and better colour rendering, more closely spaced. Only rarely is any quantitative information given about the lighting conditions created. This lack of information about the lighting conditions is understandable because all the studies described earlier have been done by criminologists rather than lighting designers, and we all tend to emphasize what we know about. Criminologists know a lot about crime but little about lighting. While it is understandable that the lack of information about the lighting used in the aforementioned studies is understandable it is nonetheless disappointing because having established that improved lighting can sometimes have an effect on the level of crime, it is now necessary to turn to the question of what are the essential aspects of lighting needed to help reduce crime. Given that a plausible basis for both of the proposed mechanisms for reducing crime is enhanced visibility, the aspects of lighting likely to be important are the average illuminance, illuminance uniformity, glare and light spectrum.

12.5.1 Illuminance

As in most lighting questions, the measure that immediately springs to mind when considering improvements in visibility is the luminance to which the visual system is adapted. This luminance is determined by the luminances of the surfaces forming the scene, which in turn are determined by the illuminances on those surfaces and their reflectances. The usual practice in street lighting is to ignore the inter-reflected light and only consider the light directly incident. This is reasonable for practice given the great diversity of situations in which street lighting is installed, but, if there are any nearby surfaces, it is worth remembering that high-reflectance, diffusely reflecting surfaces produce much more diffuse lighting. This will increase the adaptation luminance, reduce the strength of any shadows and diminish the impact of disability glare.

But what adaptation luminance, or more practically, illuminance, should be provided to facilitate adequate visibility? There are two approaches by which quantitative knowledge might be obtained. The first approach is to carry out practical tests of how far away it is possible to see various levels of detail under different illuminances. This is discussed in Section 11.5.2. The second is to measure how safe people perceive a location to be under different illuminances. Simons et al. (1987) carried out field appraisals of 12 different street lighting installations in London using a panel of observers experienced in street lighting, the assessments being made from the pedestrian viewpoint. It was established that an average horizontal illuminance of 5 lx was considered adequate and about 11 lx was seen as good. Assessments of street lighting in a much smaller city and using less experienced observers again revealed that an average horizontal illuminance of 5 lx was again considered adequate and 10 lx was considered good.

Boyce and Bruno (1999) asked people to assess the feeling of safety induced by the lighting of a large open car park. The lighting was provided by either 250 or 400 W HPS or 250 W MH light sources. The assessments were made by people wearing and not wearing spectrally neutral glasses with a transmittance of 0.11. Figure 12.1 shows the mean rating of safety in the parking area plotted against the mean illuminance on the ground. The perceived safety is clearly linked to the average illuminance on the pavement, regardless of lamp spectrum, with an illuminance of about 30 lx being required to produce a very safe rating. Conversely, illuminances less than 5 lx produced rating on the dangerous half of the scale.

A more extensive series of evaluations of street lighting as regards perceptions of safety are described in Boyce et al. (2000b). In the first study, two field surveys were carried out: one in New York City and one in Albany, the New York State capital.

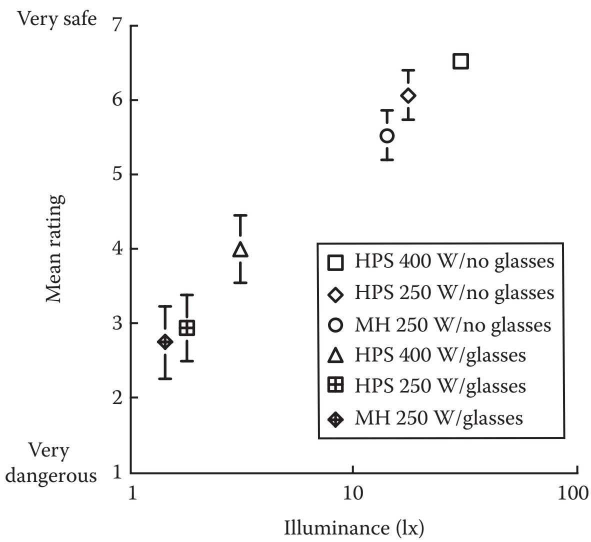


FIGURE 12.1 Mean ratings of safety provided by the lighting plotted against the mean illuminance on the pavement of a large open car park. The error bars are standard errors of the mean. Data are given for different combinations of HPS and MH lighting seen with the naked eye (no glasses) and through low-transmittance glasses (glasses). (After Boyce, P.R. and Bruno, L.D., *J. Illum. Eng. Soc.*, 28, 16, 1999.)

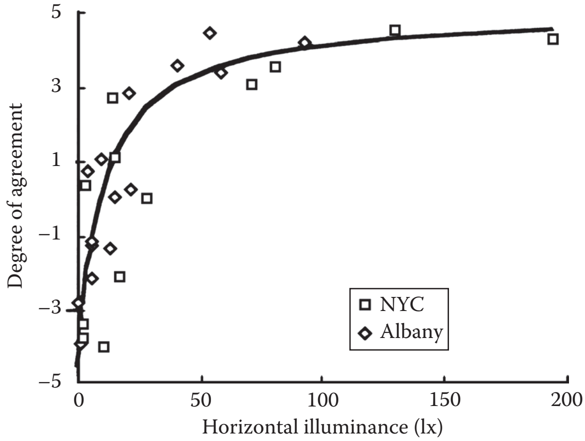


FIGURE 12.2 Mean levels of agreement with the statement 'This is a good example of security lighting' plotted against horizontal illuminance, for sites in New York City and Albany, NY. A value of +5 indicates strong agreement and −5 indicates strong disagreement. (After Boyce, P.R. et al., *Lighting Res. Technol.*, 32, 79, 2000b.)

In both cities, a number of exterior areas around multifamily housing projects, commercial strip developments and industrial buildings that were accessible to the public were selected. Each site was visited at night by a panel of people, most of whom had no knowledge of lighting. Figure 12.2 shows the mean agreement with the statement 'This is a good example of security lighting', plotted against the horizontal illuminance, 1.5 m above ground level and at the viewing position, for each site in New York City and in Albany. The degree of agreement with the statement 'This is a good example of security lighting' was highly correlated with degree of agreement with the statements 'I can see clearly around me' ($r = 0.90$) and 'I can see far enough ahead' ($r = 0.89$). Figure 12.3 shows the mean agreement with the statement 'This is a good example of security lighting', plotted against horizontal illuminance, for the male and female participants separately. It is clear that females require a higher illuminance for the same perception of good security lighting than the males. From Figures 12.2 and 12.3, it is possible to determine an illuminance necessary to achieve a perception of good security lighting. Assuming that the objective should be to have a mean agreement level of +3, that is, that the average person should moderately agree that this is a good example of security lighting, Figure 12.2 suggests an illuminance of 40 lx is required. For the same criterion, Figure 12.3 shows that an illuminance of 35 lx is required for males and 60 lx for females.

These field studies were both conducted in urban areas. The relationship between illuminance and the perception of good security lighting found in urban areas may not hold for suburban areas, where the risk of crime is less and the ambient illumination, which influences the perception of brightness, is less. Another field study was undertaken to answer this question, using outdoor car parks in an urban and an adjacent suburban area. The same methodology was used as in the previous study, with the exception that the car parks were also visited in daytime. Figure 12.4 shows the mean levels of agreement with the statement 'This is a good example of security lighting'

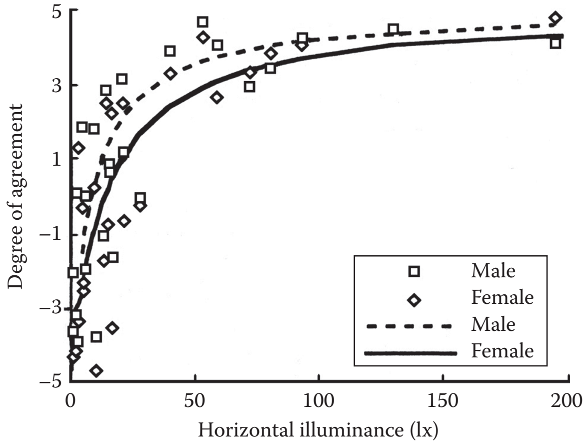


FIGURE 12.3 Mean levels of agreement with the statement 'This is a good example of security lighting' plotted against horizontal illuminance, for sites in New York City and Albany, NY, for male and female participants separately. A value of +5 indicates strong agreement and −5 indicates strong disagreement. (After Boyce, P.R. et al., *Lighting Res. Technol.*, 32, 79, 2000b.)

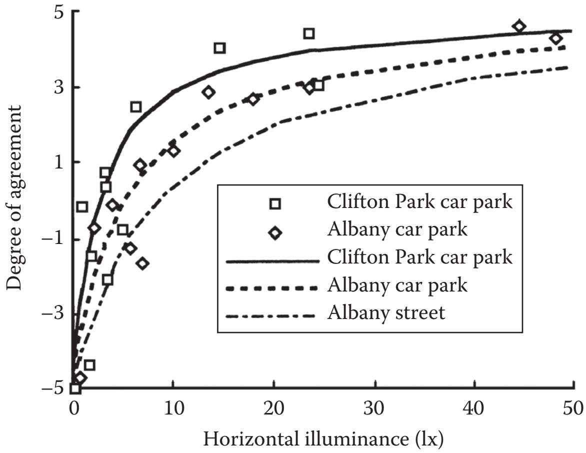


FIGURE 12.4 Mean levels of agreement with the statement 'This is a good example of security lighting' plotted against median pavement illuminance, for outdoor car parks in Albany, NY (urban), and Clifton Park, NY (suburban). A value of +5 indicates strong agreement and −5 indicates strong disagreement. Hyperbolic functions are fitted through the data for Albany and Clifton Park separately. Also shown is the hyperbolic function that fits the equivalent data for streets in Albany, NY. (After Boyce, P.R. et al., *Lighting Res. Technol.*, 32, 79, 2000b.)

plotted against the median illuminance on the ground for both urban and suburban car parks as well as the best-fitting hyperbolic curve obtained for streets in the same urban area. These results show that a lower illuminance can be used in suburban car parks to produce the same perception of goodness of security lighting as a higher illuminance in urban car parks. Further comparisons of the perception of safety in both urban and suburban car parks by night and day demonstrated that lighting can bring that perception at night close to what it is during the day but cannot exceed it. They also suggested that at a high enough illuminance, the difference in ratings of safety for day and night approaches zero. However, the approach to zero difference is asymptotic so that above 10 lx, the difference is less than one scale unit, and above 30 lx, the difference is less than half a scale unit on a seven-point scale (see Section 11.5.1).

These field studies were undertaken by different people, in different locations, using similar methods. Despite this diversity, the field studies show some similarity. Specifically, they all show a non-linear change in the explicit or implicit perceptions of safety at night with increasing illuminance. For illuminances in the range 0–10 lx, small increases in illuminance produce a large increase in perceived safety. For illuminances above 50 lx, increases in illuminance make little difference to perceived safety. For illuminances in the range 10–50 lx, increases in illuminance show a law of diminishing returns. These results suggest an average illuminance of at least 10 lx is what is required for an installation to be considered adequate security lighting. The minimum maintained average illuminance recommended for outdoor car parks in the United Kingdom covers the range 5–20 lx depending on the amount of traffic (SLL, 2012a).

12.5.2 Illuminance Uniformity

This extensive discussion of illuminance should not be interpreted as meaning that illuminance is the only aspect of lighting that matters to the perception of safety at night. The variability in perceived safety at night, particularly at low illuminances (see Figures 12.2 through 12.4), suggests that there are other factors operating in addition to illuminance. For example, it is widely believed that uniformity of illuminance and the presence of disability glare also matter to perceptions of safety. Concern with illuminance uniformity is reasonable because if lighting is effective because it allows better surveillance, then the presence of areas lit to a much lower illuminance in which criminals can lurk without being seen is likely to prove damaging to a perception of safety. Despite this argument, evidence for a uniformity criterion is notable by its absence. However, illuminance uniformity recommendations are still made based on experience. For example, in the United Kingdom, the minimum illuminance uniformity ratio (minimum/average) recommended for outdoor car parks is 0.25 (SLL, 2012a).

The main cause of poor illuminance uniformity is the overspacing of luminaires and the shadows cast by buildings and vegetation. Shadows and vegetation can be dealt with by careful positioning of luminaires and regular maintenance of the area, but overspacing is a matter of lighting design. Reputable manufacturers of lighting equipment specify a maximum spacing for a given mounting height. These limits should be strictly observed.

Haans and de Kort (2012) have examined a particular form of illuminance nonuniformity in the context of dynamic outdoor lighting. Dynamic outdoor lighting using LEDs as a light source has been proposed as a means of energy saving. The energy savings arise because the lighting is dimmed in areas remote from the pedestrian. Thus, as the pedestrian walks along the street, successive luminaires are brought to full light output, returning to the dimmed state after the pedestrian has passed, a process whereby the lighting matches the progress of the pedestrian along the street. Haans and de Kort (2012) examined peoples' perceptions of safety under such a lighting installation when walking along the street. They found that safety was perceived to be least when the illuminance immediately around the pedestrian was low (0.5 lx) although more distant parts of the street were well illuminated (12.5 lx). Perceptions of safety were much better when the street within about 30 m of the pedestrian was illuminated to a high illuminance (9.5–12.5 lx). This implies that illuminance uniformity matters and it is the zone around the pedestrian that matters most.

12.5.3 Glare

There is no direct information on the effect of glare from street lighting on people's ability to detect and recognize people approaching them. Rombouts et al. (1989) calculated the effect of glare from street lighting using the measure of disability glare commonly used for drivers, the threshold increment (see Section 10.4.2). Using this approach, they found that the minimum semi-cylindrical illuminance for confident facial recognition at 4 m increased from 0.4 to 0.6 lx when the street lighting luminaires produced a threshold increment of 15%. This very limited evidence suggests that disability glare is unlikely to be a problem for law-abiding pedestrians as long as street lighting is designed to existing criteria.

Against this, Simons et al. (1987) doubt whether threshold increment is a suitable measure of the effects of disability glare on pedestrians because the state of adaptation of the driver might be different from that of the pedestrian and the restriction of the driver's field of view imposed by the roof of the car limits the view of some of the luminaires. Simons et al. (1987) recommend limiting disability glare by restricting the luminous intensity distribution of street lighting luminaires to maxima of 175 and 100 cd/klm at 80° and 90° from the downward vertical, respectively. How effective these limits are will depend on the mounting height of the luminaires.

Another approach is to use the Commission Internationale de l'Eclairage glare rating system adopted for sports lighting (CIE, 1994c). The glare rating is given by

$$GR = 27 + 24\log_{10}\left(\frac{L_{VL}}{L_{VE}}\right)$$

where

GR is the glare rating

L_{VL} is the equivalent veiling luminance (cd/m^2) due to the luminaires

L_{VE} is the equivalent veiling luminance (cd/m^2) due to the rest of the visual environment

The glare rating will vary with position and direction of view so it will be necessary to calculate the glare ratings for all important locations. The problem with this approach is that estimating L_{VE} can be complex. CIE (1994c) suggests a simplified method in which L_{VE} is equated to 0.035 L_{AV} where L_{AV} is the average luminance (cd/m^2) of the horizontal area seen by the observer. The SLL Code for Lighting (SLL, 2012a) recommends that the glare rating should not exceed 50–55 for car parks.

12.5.4 Light Source Colour

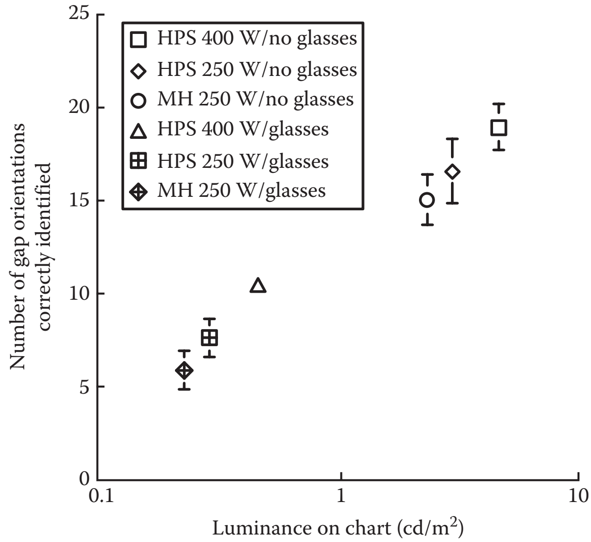
There are three reasons why the colour properties of the light source used might be important to the effectiveness of lighting for surveillance. The first is that in mesopic conditions, which can occur under outdoor lighting, light sources that more effectively stimulate the rod photoreceptors will make off-axis visual detection better (see Section 10.4.3) The second is that where there are colours in the scene, light sources with better colour-rendering properties will create larger colour differences. Such colour differences improve visual performance when luminance contrast is low (O'Donell et al., 2011). The third is the fact that colour is an important element in witness descriptions. Light sources with good colour-rendering properties will allow more accurate colour naming (Boyce and Bruno, 1999).

While these arguments suggest that light source colour properties ought to be important to surveillance, evidence that such properties make a difference is difficult to come by. For example, Boyce and Rea (1990) showed that the probability of detecting a person approaching along a known path and the recognition of their face is the same under both LPS and HPS lighting of the same vertical illuminance. LPS light sources are essentially monochromatic and so give no colour information. HPS light sources, while far from perfect, do give much clearer colour perception. These results would seem to imply that light source colour is not important for the detection and recognition of people approaching.

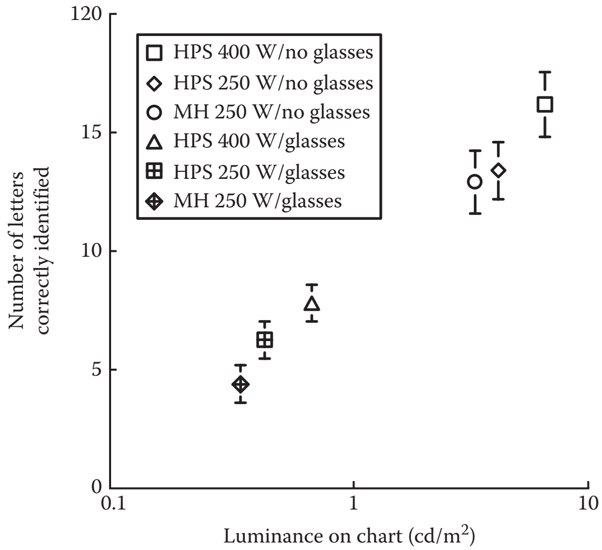
Another study that examined the effect of light source colour on the perception of safety under different light sources was that of Boyce and Bruno (1999). This study involved the performance of a number of tasks and the collection of opinions on the lighting of a large outdoor car park that could be divided into three approximately 1000 m^2 areas. Each area was lit by the same number of new luminaires fitted with either HPS or MH lamps. At two locations in each bay, the participants' visual acuity and contrast threshold were measured using charts with Landolt rings of a fixed luminance contrast and reducing size and letters of fixed size but decreasing luminance contrast, respectively. In addition, the participants gave their opinions of the lighting on various dimensions. While doing the tasks and answering these questions, the participants were seated in a car looking down the length of one of the driving aisles, wearing and not wearing grey wraparound glasses with a transmittance of 0.11. When the glasses were worn, the subjects' state of adaptation was mesopic.

Figure 12.5 shows how the number of Landolt rings whose orientation was correctly identified and the number of letters correctly read vary with the different lighting conditions. Clearly, the dominant factor in the performance of these black and white tasks is the luminance on the charts. Light spectrum has no obvious effect. Eloholma et al. (1999a) have found similar results for high- and low-contrast visual acuity over a luminance range of 0.19–5.2 cd/m^2.

Another task required the observer to identify objects carried by a person in the car park. Under each lighting condition, the subjects were asked to identify whether



(a)



(b)

FIGURE 12.5 (a) The mean number of Landolt ring gap orientations correctly identified plotted against the luminance of the visual acuity chart background and (b) the mean number of letters correctly identified on the contrast threshold task plotted against the luminance of the chart background. The error bars in both graphs are standard errors of the mean. Data are given for different combinations of HPS and MH lighting seen with the naked eye (no glasses) and through low-transmittance glasses (glasses). (After Boyce, P.R. and Bruno, L.D., *J. Illum. Eng. Soc.*, 28, 16, 1999.)

a person about 10 m away was carrying a metal ruler, a hammer, a spanner, a spray can, a screwdriver, a torch, a beer bottle, a gun, an umbrella, a knife or a pair of scissors. The mean number of objects correctly identified out of a maximum possible of five is closely related to the illuminance in the car park, independent of light spectrum (see Figure 11.13).

The only task that did show a clear effect of light spectrum is that of colour naming. The subjects were shown nine matte Munsell colour plates, the nine colours being the basic colours identified by Boynton and Olson (1987). Figure 12.6 shows the mean percentage of colours correctly identified. The MH light source produces a higher percentage correct naming than the HPS light sources, even though the former produces a lower illuminance on the colours. However, it is worth noting that increasing the illuminance does improve the percentage correct colour naming for the HPS light sources, so correct colour naming at low light levels is a matter of both light spectrum and illuminance.

But how relevant is colour naming? One situation in which colour is believed to be important is for eyewitness accounts of a crime. Rea et al. (2009a) carried out a study of the effect of illuminance and light spectrum on the ability of people to recall a scene. In this, an observer saw two groups of seven people standing on either side of an isolated road lit by either HPS or MH lighting to either 5 lx or 15 lx. All the people in these two groups were individually marked with a two-colour patch attached to their jackets and a black and white number on their backs. These two groups repeatedly crossed the road. One of these people was carrying a blue- and yellow-coloured American football. After 30–40 s of crossing, the person carrying the football was

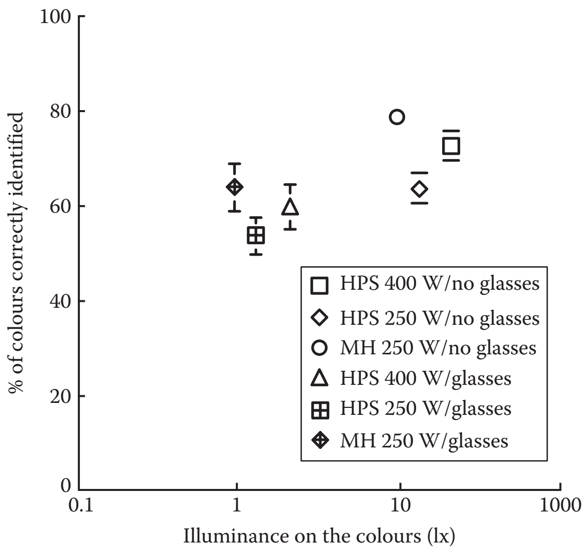


FIGURE 12.6 Mean percentage of colours correctly identified plotted against the mean illuminance on the colours. The error bars are standard errors of the mean. Data are given for different combinations of HPS and MH lighting seen with the naked eye (no glasses) and through low-transmittance glasses (glasses). (After Boyce, P.R. and Bruno, L.D., *J. Illum. Eng. Soc.*, 28, 16, 1999.)

asked to raise it up and pass it to one of the others. After this, the observer was asked to look away and to describe the person who passed the football and the person who received it, using a questionnaire asking for different types of information. The questionnaire asked about gender, ethnicity, height, body type, hair colour and length, type and colour of clothing, colours and number of the markings, facial hair and any head coverings. Out of 13 pieces of information, only 5 showed a statistically significant effect of illuminance or light spectrum. Apart from gender, recall was poor although what there was demonstrated that recall of the scene was more accurate under 15 lx than under 5 lx and better under MH lighting than HPS lighting.

The implication of these results is clear; in order to see detail, to recognize people approaching and to see what they are carrying, the light spectrum matters little. What does matter is the illuminance. This is probably because such tasks require the use of foveal vision. It is only when colour is relevant to the performance of foveal tasks that light spectrum has a role to play. This conclusion should not be taken to mean that light spectrum does not matter at all. There is no doubt that light spectrum has a significant effect on off-axis detection (see Section 10.4.3) and, when luminance contrast is low, colour difference is important to visual performance (see Section 4.3.6). Unfortunately, the conditions commonly occurring in car parks and on streets are not always conducive to such effects. While low-luminance contrasts are quite common on streets and in car parks, the saturated colours required to produce large colour differences are not. The one effect of light spectrum that is likely to occur frequently is spatial brightness. As discussed in Section 11.5.1, light spectra that have a high scotopic/photopic (S/P) ratio produce a greater perception of spatial brightness than those with a low S/P ratio at the same illuminance, and the perception of spatial brightness is closely linked to the perception of safety (Rea et al., 2009a). What this means is that using a light source with a high S/P ratio to provide the recommended illuminance will be the best approach to ensure a perception of safety. Reducing the illuminance when a light source with a high S/P ratio is used can maintain the perception of spatial brightness and probably safety, but there is a risk that the ability to see detail and recognize people approaching will be degraded.

12.5.5 Design Approaches

The discussion above makes it possible to specify what constitutes good lighting for facilitating surveillance in photometric terms, although some parts of the specification are more soundly based and more important than others. The mean illuminance on the pavement should be in the range of 10–50 lx, the overall illuminance uniformity ratio should be better than 0.25, the glare rating should be less than 50 and a good colour-rendering source should be used, especially if a wide range of colours is present. Different design approaches can be used to meet this specification but not all will be effective. One to be avoided is the use of bollards. These luminaires are typically about 1 m high and direct light onto the ground. This is appropriate where the objective of the lighting is to light the path so that people do not trip and fall, but for a perception of safety, it is necessary to light the whole of anyone approaching and not just their knees. A much more common approach in pedestrianized areas is to use post-top luminaires. These typically have the light source at a height of 3–6 m. Post-top luminaires can be very effective but care has to be taken to limit the luminance of the light source so glare is avoided, and the luminaires have to be spaced close enough so that a person standing under one luminaire also receives light from others. If this is not done, as a person walks past a luminaire, they change from being well illuminated when approaching the luminaire to a featureless silhouette as they pass the luminaire.

Another approach often used around buildings is the ubiquitous wall pack. Typically, these are mounted on the wall of the building at 3–6 m. This low mounting height makes the wall pack a potential glare source. Glare can be avoided by choosing a wall pack which does not allow a direct view of the light source. Similar advice applies to post-top luminaires. Finally, there are arrays of parking lot luminaires that are typically mounted at 6–15 m. The higher is the mounting height, the less likely it is that glare will occur and the more likely that the desired illuminance uniformity will be achieved. For lower mounting heights, care must be taken to limit the luminous intensity distribution at high angles from the downward vertical. Details of exterior lighting installations designed to combat crime and that are suitable for many different contexts can be found in Leslie and Rodgers (1996). These designs also demonstrate that lighting that can be effective in reducing crime need not be ugly. Indeed, such lighting can be attractive.

12.6 SPECIAL SITUATIONS

All the above discussion has been focused on the impact of lighting on areas to which the public has access and where the main means of detecting crime is the human visual system. It is now necessary to consider how lighting might act as a countermeasure against crime in protected locations and where surveillance through CCTV is used.

12.6.1 Fenced Areas

It is common practice to protect valuable property by fences and to patrol the fence either from inside or outside the site. Lighting is provided for the people patrolling the fence. If the patrolling is done from inside the fence, the lighting is designed to light both sides of the fence so that anyone approaching the fence or any damage to the fence can be seen. The rest of the site may be lit or it may not. If the patrolling is done by the police from the outside, then the whole of the site, including the fence, is usually lit. The problem of lighting the fence is how to make it easy for the patrolling guard to see through the fence. The fence is usually a lot closer to the light source than the area that the guard needs to see. This means that there is a risk that the luminance of the fence will be higher than the luminance of the area seen through it. Boyce (1979b) showed that the ability to detect someone through a fence was greatest when the luminance of the fence matched or was less than the luminance of the surface being viewed through the fence. Fence luminances higher than the luminance of the area outside the fence reduce the visibility through the fence. This reduction is greater for smaller fence mesh sizes. This understanding can be used to either increase or decrease visibility through a fence. Where it is desired to increase visibility through the fence, the luminance of the fence should be kept low. This can most easily be achieved by using low-reflectance materials for the fence. Where it is desired to make the visibility through a fence difficult, high-reflectance materials should be used for the fence.

12.6.2 Gatehouses

Every fenced area has a means of access, usually protected by a guard in a gatehouse. The role of the guard is to check people and vehicles arriving and departing and to make sure nobody gets in who should not. Lighting designed to help with the inspection of people and vehicles, including the underside, is a common feature of gatehouse lighting (Lyons, 1980). The average illuminance recommended for the area immediately outside a gatehouse is much higher than for the rest of the site, 100 lx being typical. The most common failing of gatehouse lighting is the excessive amount of light inside the gatehouse after dark. This enables any would-be offender to see into the gatehouse and determine what the guard is doing. To avoid giving the game away, it is necessary to use only the minimum amount of light in the gatehouse after dark. It would also be possible to make seeing into the gatehouse difficult by covering the windows with a mesh of high reflectance on the outer surface and then lighting that surface. The inner surface should have a low reflectance.

12.6.3 Unfenced Areas

Sometimes, it is desired to protect a large open area but the cost of fencing the area is prohibitive. One approach to solving this problem is to use glare lighting (Lyons, 1980). Glare lighting is designed to provide the maximum amount of disability glare to anyone approaching the line of glare sources. Therefore, the luminaires are usually mounted at eye height and aimed so that the maximum luminous intensity occurs horizontally out from the protected area. Glare lighting is rarely used because it is not popular with the neighbours and it is only effective when the site behind the line of glare luminaires is completely dark and there is some possibility that there might be a guard who cannot be seen behind the line of glare sources.

12.6.4 Facade Lighting

Buildings on both fenced and unfenced sites are usually protected by means of locks on doors, bars on windows and alarms. Lighting of the building's facade is sometimes used as part of this system of protection. The idea of facade lighting is that it enables anyone tampering with the doors or windows to be seen from a distance. Facade lighting will only be effective if it is comprehensive, that is, it covers the entire facade uniformly, without glare. In this situation, anyone attempting to break into the building can be seen in silhouette against the wall. The completely opposite approach is sometimes used, namely, to eliminate all lighting in and around the building. This has the effect of making the building inconspicuous and the presence of any lighting indicates illegal activity. The problem with this approach is that some illegal activities can be undertaken with very little light. There is no right or wrong answer to this problem. The designer has to make a choice on the best approach to use depending on the type of illegal activity expected, the level of risk and the system of protection proposed.

12.6.5 Closed-Circuit Television

In recent years, CCTV has become ubiquitous. As with improved lighting, the effect of CCTV systems in reducing crime has been mixed, depending on the circumstances (Welsh and Farrington, 2002). The role of lighting in CCTV surveillance is to allow the camera to provide clear pictures. Exactly how much light is needed and what the ideal light spectrum is depends on the characteristics of the camera. Available CCTV devices cover a large range of sensitivities, from a minimum illuminance of 10 lx to the very low illuminance provided by starlight alone. As for spectral sensitivity, most CCTV cameras do not have the same spectral sensitivity as the human visual system, usually being much more sensitive to infrared radiation. Before selecting a camera, it is always necessary to check that the proposed light source will provide enough radiation for the camera to operate successfully.

Having determined the amount and spectral content of the lighting to be used with a specific camera, it is then necessary to decide on the light distribution. Care has to be taken with distribution because the one thing all CCTV cameras have in common is a limited dynamic range. This means that too large a range of luminance will lead to areas of the image being black while other areas are white. In both black and white areas, no detail can be seen. The first rule to limit the range of luminances is to keep all light sources out of the field of view of the camera. For exteriors, this means keeping the sun and any luminaires out of the field of view. For interiors, this means keeping windows and luminaires out of the field of view. The second is to provide lighting that is uniform and avoids shadows on faces. Hargroves et al. (1996) examined the impact of different light distributions on the CCTV image of a face, the light distributions being characterized by a series of illuminance and luminance ratios. They identified two critical ratios for an acceptable appearance of a CCTV image of a face. The first was the ratio of the illuminance on the top of the head to the illuminance on a plane containing the face, the normal to the plane being in the direction of the camera. The maximum value of this illuminance ratio for acceptable CCTV images was 5.0. Illuminance ratios larger than 5.0 tend to produce strong shadows under the eyes, nose, mouth and chin which distort the appearance of the face. The second ratio was the average luminance of the face to the average luminance of the background against which the camera sees the face. The range of values of this ratio for acceptable CCTV images was from 0.3 to 3.0. When the luminance of the background against which the face is seen is too high, so that the luminance ratio is less than 0.3, the image of the face will be very dark. If the luminance of the background is too low, so that the ratio is more then 3.0, the image of the face will be washed out. For interiors, the simplest way to meet these two ratios is to use indirect lighting and to position the camera so that it does not have a window in its field of view. The likelihood of getting a good CCTV image is further increased by using medium reflectance wall finishes and a floor reflectance of 0.20. Lighting installations using direct lighting luminaires with a narrow luminous intensity distribution in a low-reflectance room are guaranteed to produce poor CCTV images. For exteriors, indirect lighting is not possible, but the same criteria apply. Fortunately, lighting that facilitates visual surveillance by people in the area should also be effective in meeting the criteria for a good CCTV image, namely, lighting that provides a uniform illuminance over a large area, without glare.

12.7 GENERALIZATION AND VALUE

One feature of the study of the effects of lighting on the prevalence of crime that marks it out as different from other areas of lighting research is the fact the most of the studies has been done in the United Kingdom and United States. Given this situation, the question naturally arises as to whether the conclusions reached can be generalized to other countries where the conditions and culture are different. The answer is a definite maybe. It is not possible to be more definite without studies done in other countries but the conditions for successful generalization can be defined. The important point is that lighting, *per se*, has no direct effect on crime. Rather, it has an indirect effect by facilitating surveillance, community confidence and social control. In countries or communities where criminals consider increased surveillance makes criminal activity more risky and less rewarding, and where public lighting is inadequate for good surveillance, improving lighting sufficiently to ensure good surveillance can be expected to reduce criminal activity. In countries where criminals are not bothered about surveillance, either because the community is intimidated by or supports the criminals, or there is little prospect of action by the authorities, improving the lighting to enhance surveillance will be ineffective.

One other point to consider is the value of improving lighting in terms of its cost-effectiveness. Painter and Farrington (2001b) consider this question, using estimates of the cost of individual crimes to the victims and to the authorities and the costs of improving the lighting. Based on their studies in Dudley (Painter and Farrington, 1997) and Stoke-on-Trent (Painter and Farrington, 1999), they conclude that the financial benefits of better street lighting due to the reduction in crime can enormously outweigh the financial costs of providing the lighting. Specifically, they estimate that the financial benefits of reduced crime are enough to cover the capital costs of improving the lighting within 1 year, even when only tangible costs are considered. Of course, this conclusion is based on British costs but, in general, such a finding is good news for all those who believe in the value of lighting.

12.8 SUMMARY

Attempts to use lighting as a means to reduce or at least limit criminal activity have a long history. Starting in the fifteenth century, major cities in Europe attempted to provide some form of exterior lighting at night, either by requiring householders to provide luminaires on their property or by a developing a system of public lighting controlled by the authorities. Since that time, the provision of public lighting has become more sophisticated, more widespread and more centralized until today virtually all cities, towns and villages in the developed world have some form of public lighting. This public lighting can fulfil many roles. The role considered here is that of crime prevention.

A series of studies of increasing sophistication leave little doubt that lighting can play a part in crime prevention, but it may not always be effective. There can be no guarantees. This is because lighting, *per se*, does not have a direct effect on the level of crime. Rather, lighting can affect crime by two indirect mechanisms. The first is the obvious one of increasing visibility, thereby facilitating surveillance by people on the street after dark, by the community in general and by the authorities. If such increased surveillance is perceived by criminals as increasing the effort and risk and decreasing the reward for a criminal activity, then the incidence of crime is likely to be reduced. Where increased surveillance is perceived by the criminally inclined not to matter, then better lighting will not be effective. The second indirect mechanism by which an investment in better lighting might affect the level of crime is by enhancing community confidence and hence increasing the degree of informal social control. This mechanism can be effective both day and night but is subject to many influences other than lighting.

Unfortunately, many of the studies that demonstrate the value of better lighting as regards reduced levels of crime contain few details of the lighting necessary to achieve the desired effect. However, in these studies, better lighting usually involves the use of more light sources with higher light output and better colour rendering, more closely spaced. From such information and basic knowledge of how to make it easier to see details at night, it can be concluded that the important factors are the illuminance provided, the illuminance uniformity, the control of glare and the light spectrum. From a combination of experimental studies and practical experience, it is possible to specify what constitutes good lighting for facilitating surveillance, although some parts of the specification are more soundly based and more important than others. In public pedestrianized areas, the mean illuminance on the pavement should be in the range of 10–50 lx, the overall illuminance uniformity ratio should be more than 0.25, the glare rating should be less than 50 and a good colour-rendering source should be used, especially if a wide range of colours is present. Lighting meeting this specification should allow anyone on the street to detect and recognize a threatening situation while there is still time to do something about it which will, in turn, do something to reduce the fear of crime.

While most of this chapter is devoted to the lighting of areas to which the public has access, lighting can also be used to protect private areas. For example, lighting can be used to increase or decrease visibility through a fence. Visibility will be enhanced when the luminance of the fence is the same as the luminance of the area seen through the fence. Visibility will be reduced when the luminance of the fence is much higher than the luminance of the area being viewed through the fence. Lighting can also be used to enhance the performance of remote surveillance based on a CCTV system. The amount and spectrum of the light needed will depend on the characteristics of the CCTV camera used, but one factor that requires attention for all CCTV systems is the light distribution. CCTV cameras all have a limited dynamic range so they provide the best images when the range of luminances in their field of view is limited and shadows are avoided on significant features, such as faces.

There remains much to be understood about what conditions are necessary for lighting to be effective in reducing crime in different countries, but one thing is clear, it can be done.

13 Lighting for the Elderly

13.1 INTRODUCTION

Given the alternative, everyone should look forward to being old. With increasing age comes knowledge and, in some cases, wisdom. Unfortunately, knowledge and wisdom have companions in the form of physical and mental decline, ultimately leading to loss of independence, dementia and death. This chapter examines the changes that occur in the visual system and the circadian timing system with increasing age, the consequences of these changes and how lighting can be used to offset some of them so that the quality of life of the elderly may be sustained.

13.2 OPTICAL CHANGES WITH AGE

The human visual system can be considered as an image-processing system. Like all such systems, the visual system is most effective when it is operating at an appropriate sensitivity with a clear retinal image to process. The factors that determine the operating state of the visual system are the amount of light that reaches the retina and the wavelengths from which it is constituted. The factors that determine the clarity of the retinal image are the ability to focus the image of the external object on the retina, the extent to which light is forward scattered as it passes through the eye and the presence of stray light produced by back reflection from the components of the eye, transmittance through the eye wall and fluorescence in the lens of the eye (Boynton and Clarke, 1964; van den Berg et al., 1991; van den Berg, 1993). Virtually, all these characteristics change with age (Weale, 1992; Werner et al., 2010).

In simple optical terms, the eye has a fixed image distance and a variable object distance. To bring objects at different distances to focus on the retina, the optical power of the eye has to change. The optical power of the eye is determined by the curvature of the cornea, which is fixed, and the thickness of the lens, which is variable. If there is a mismatch between the distance of the retina from the lens and the combined optical power of the cornea and lens, the image of the outside world will not be in focus on the retina so the resulting retinal image will be blurred. Blur has been shown to be a potent cause of reduced visual performance (Johnson and Casson, 1995). The range of object distances that can be brought to focus on the retina decreases with age, because of increasing rigidity of the lens. After about 60 years of age, the eye is virtually a fixed focus optical system (Figure 13.1). Spectacles or contact lenses are commonly used to modify the optical power of the eye, the prescription of the spectacles or contact lens changing over the years as the lens becomes increasingly rigid.

The optical factors determining the amount of light reaching the retina are the pupil size and the spectral absorption of the components of the eye. The area of the pupil varies as the amount of light available changes, the pupil opening to admit

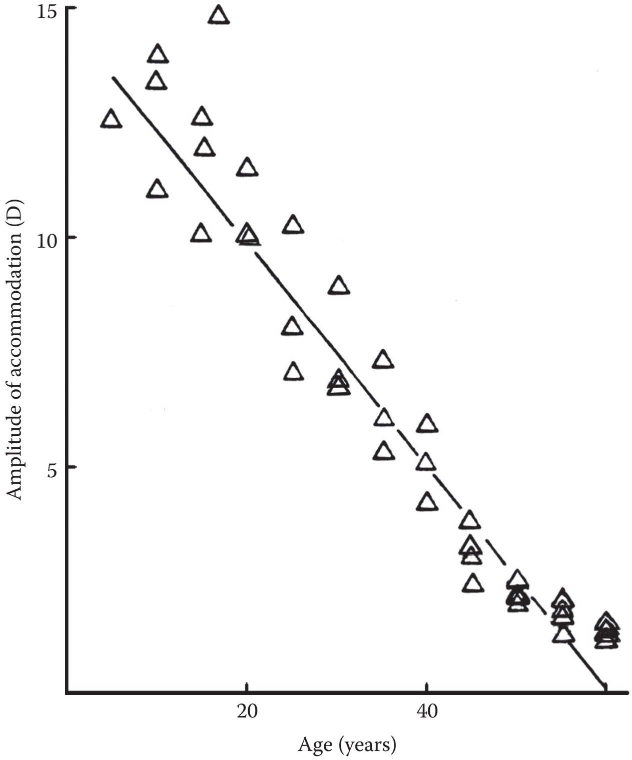


FIGURE 13.1 The variation of the amplitude of accommodation with age. The amplitude of accommodation is measured in dioptres, the difference between the reciprocals of the shortest and longest distances from the eye at which a sharp retinal image can be achieved, the distances being measured in metres. (After Weale, R.A., *Mech. Ageing Dev.*, 53, 85, 1990.)

more light when there is little and closing when there is plenty. The ratio of maximum to minimum pupil area decreases with age, the maximum decreasing much more than the minimum (Figure 13.2). This means the elderly are much less able to compensate for low light levels by opening their pupils than are young people.

As for the spectral absorption of the eye, the majority of absorption takes place on passage through the lens (Murata, 1987). The absorbance of the human lens increases exponentially from birth, following the formula (Weale, 1992)

$$D = D_0 e^{bA}$$

where

D is the absorbance

D_0 is the absorbance at birth

β is a constant that varies with wavelength

A is the age in years

Using this formula and the values for D_0 and β given in Weale (1988), it is possible to calculate the absorbance of the lens over a range of visible wavelengths,

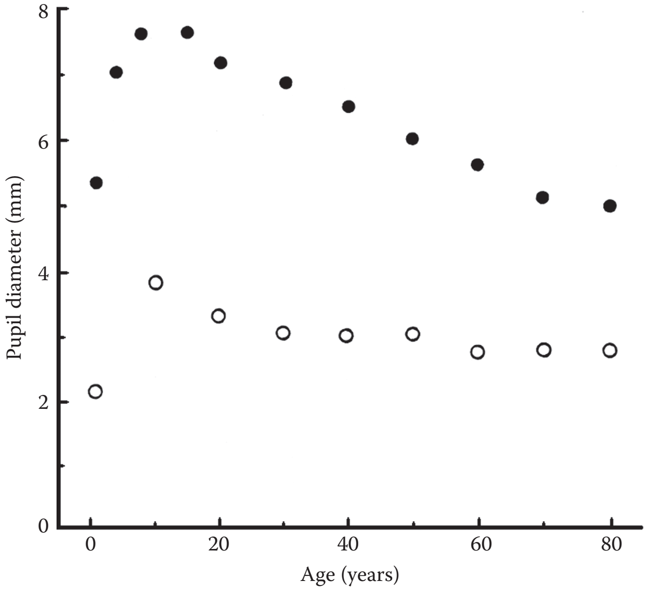


FIGURE 13.2 Maximum and minimum pupil diameters as a function of age. (After Weale, R.A., *A Biography of the Eye: Development, Growth, Age*, H.K. Lewis, London, U.K., 1982.)

for different ages (Figure 13.3). From Figure 13.3, it can be seen that the absorbance at short wavelengths increases dramatically with age. This goes some way to explain the diminished colour vision capabilities of elderly people. Investigation of the causes of this increased absorbance with age has demonstrated that the change occurs primarily in the nucleus of the lens (Mellerio, 1987). This implies that the spectral absorbance of the lens will also vary with pupil size, smaller pupil sizes leading to greater absorbance (Weale, 1991). There can be little doubt that the reduction in pupil size and the increased absorption of light during its passage through the lens reduce the retinal illumination of older people, particularly at short wavelengths.

In addition to absorbing light, transmission through the lens and the other optical components of the eye scatters light. This is important because, whereas increased absorption does not degrade the retinal image and can be compensated by providing more light, scattered light degrades the retinal image and providing more light does not help. Scattered light degrades the retinal image by reducing the difference in luminance either side of an edge, thereby reducing the magnitude of its higher spatial frequencies. Scattered light also degrades the retinal image in terms of colour by adding wavelengths from one area onto another, thereby reducing the colour difference at the edge. The scattering occurring in the eye is primarily large-particle scattering, so is largely independent of wavelength. Measurements have shown that about 30% of scattering occurs at the cornea (Vos and Boogaard, 1963), with most of the rest occurring at the lens, vitreous humour and fundus (Boettner and Wolter, 1962). The amount of scatter increases with age, due mainly to changes in the lens (Wolf and Gardiner, 1965).

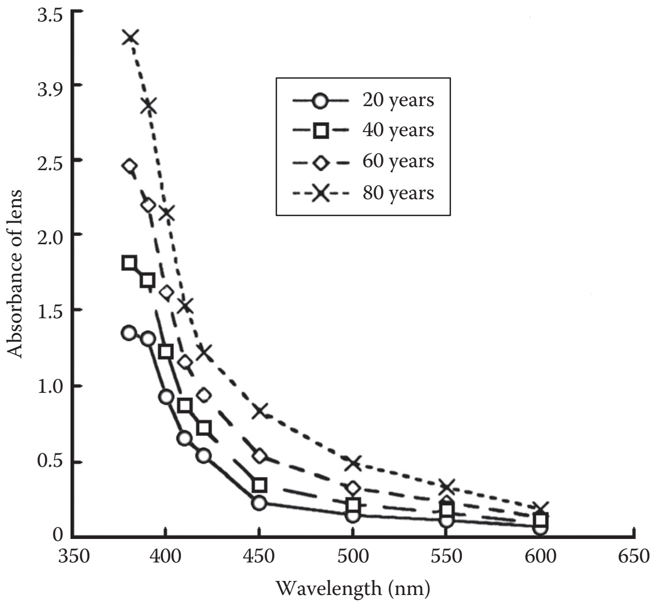


FIGURE 13.3 Spectral absorbance of the lens plotted against wavelength, for different ages. (After Weale, R.A., *J. Physiol.*, 395, 577, 1988.)

Scatter can be quantified by a point spread function, which typically shows that the amount of scattered light decreases with increasing deviation from the beam of light being scattered (Vos and Boogaard, 1963). Stray light is characterized by a homogenous distribution of luminance over the whole retinal image. Stray light within the eye is caused by light back-reflected from the retina and pigment epithelium, by transmission of light through the iris and the eye wall and by lens fluorescence. Stray light matters because it falls uniformly across the retinal image, thereby reducing the luminance contrast of all edges and the saturation of all colours in the image. The amount of stray light generated by these causes increases with age. This is particularly so for lens fluorescence. The effect of lens florescence is negligible in young eyes, but as aging continues, the luminance of stray light due to fluorescence increases and fluorophores with emission wavelengths in the most sensitive part of the visual spectrum emerge. The effect of lens fluorescence can be seen as a haze over the visual scene (Jacobs and Krohn, 1976; Weale, 1985). Lighting has a limited role to play in overcoming these optical changes by providing enough light of the right spectrum and free from glare so as to enhance the quality of the retinal image as much as possible.

The circadian timing system is just one of the non-image-forming systems but it is the one that has been most extensively examined (see Section 3.3). As a non-image-forming system, it is not influenced by the quality of the retinal image but it is influenced by the amount, spectrum, timing and duration of exposure to light. This, in turn, implies that the only age-related optical changes that are of importance for the functioning of this circadian system are the increased absorption of light, particularly at the short-wavelength end of the visible spectrum.

Whether or not the retinal image is out of focus or light is scattered or there is excessive stray light is of little concern. Using lighting to increase exposure to the short-wavelength end of the visible spectrum should be an effective means of overcoming the optical changes with age as far as the circadian timing system is concerned.

13.3 NEURAL CHANGES WITH AGE

The optical changes that occur with age affect the quality of the retinal image, but for the visual system to be effective, the retinal image has to be processed by the retina and the visual cortex. There is no reason to suppose that aging is limited to only the optical elements of the visual system. Indeed, morphological changes have been reported in rod and cone photoreceptors in older people (Marshall et al., 1979), and the densities of cone and particularly rod photoreceptors have been shown to decrease with increasing age (Curcio et al., 1993). As for the visual cortex, studies have shown reduced contrast sensitivity and spatial resolution for cortical neurons in aged monkeys with visual systems similar to humans (Zhang et al., 2008). These changes mean that both optical and neural factors are likely to be involved in the changes in visual capabilities that occur with age. Owsley (2011) concludes that the balance between the optical and neural factors is different for different visual functions. For example, she argues that in photopic conditions, changes in contrast sensitivity with age are primarily due to optical factors, but in mesopic and scotopic conditions, neural factors are more important. Therefore, lighting may have a role to play in overcoming the neural changes with age by providing enough light that their impacts are minimized.

Neural changes with age also occur in the non-image-forming systems. The density of retinal ganglion cells decreases with age (Curcio et al., 1993) and there is evidence of degeneration in the suprachiasmatic nuclei (Weinart, 2000). Such changes inevitably affect the performance of the circadian timing system.

13.4 VISION LOSS

Both the optical and neural changes discussed above are part of the normal process of aging. Everyone who lives long enough will experience these changes, but with increasing age there is also an increased probability of pathological change occurring in the eye. These pathological changes can lead to vision loss and, ultimately, blindness. Before discussing what these pathological changes are, it is necessary to define what is meant by vision loss and blindness. The accepted international definition of these terms is based on a classification of vision developed by the World Health Organization (WHO, 1977) (Table 13.1). This classification system uses the visual acuity of the better eye after optical correction for refraction error, and the size of the central visual field, to discriminate between different levels of visual loss. Visual acuity is expressed as the ratio of two distances, for example, 20/200 or 6/60. The numerator is always 20 or 6 and refers to the distance, in feet or metres, respectively, from which the person being tested looks at a test chart and determines the smallest size of target where the detail can be resolved, for example,

TABLE 13.1
WHO Classification of Vision

Category	Grade	Criteria
Normal vision	0	20/25 or better
Near normal vision	0	20/30 to 20/60
Low vision		
Moderate visual impairment	1	20/70 to 20/160
Severe visual impairment	2	20/200 to 20/400
Blindness		
Profound visual impairment	3	20/500 to 20/1000 or a visual field between 10° and 5°
Near-total visual impairment	4	Worse than 20/1000 or a visual field less than 5°
Total visual impairment	5	No light perception

Source: After World Health Organization (WHO), *Manual of the International Classification of Diseases, Injuries and Causes of Death*, WHO, Geneva, Switzerland, 1977.

a letter can be correctly identified. The denominator is the distance at which a person with normal vision can be expected to resolve the same detail. A person with best-corrected visual acuity of 20/200 (6/60) has severe visual impairment, that is, vision loss. A person with a best-corrected visual acuity of 20/20 (6/6) has normal vision. Using this classification system, the WHO has defined blindness as a best-corrected visual acuity of worse than 20/400 (6/120) or a central visual field diameter of less than 10° in the widest meridian of the better eye. Despite this international definition, there are significant national variations in the criteria for what constitutes vision loss and blindness, often because these criteria are associated with access to financial support provided by the state. For example, in the United States, the legal definition of blindness is a best-corrected visual acuity of 20/200 and a visual field of less than 20°. There are two important points to note from this discussion. The first is that normal vision, vision loss and blindness are not discrete states but rather a continuum, and the borders between these states are somewhat arbitrary. The second is that some people who are classified as blind actually have some very limited vision.

There have been many attempts to quantify the prevalence of vision loss and blindness in different populations (Tielsch, 2000; Evans et al., 2002; Bunce and Wormald, 2006). Probably, the most interesting one for the purposes of this chapter is the Baltimore Eye Survey. This survey examined 5308 residents of 40 years or older in an urban area in the United States. Table 13.2 shows the measured prevalence of blindness and vision loss for different age and racial groups. From Table 13.2, it can be seen that the prevalence of blindness and vision loss is strongly related to age and more loosely linked to race. Specifically, the prevalence of vision loss increases dramatically after about 70 years of age, and that increase seems to occur earlier for blacks than whites. As for the causes of blindness and vision loss, Table 13.3 shows

TABLE 13.2
Prevalence per 100 People of Blindness and Vision Loss for Different Age Groups and Races

	Blindness		Vision Loss	
Age Range (Years)	**Whites**	**Blacks**	**Whites**	**Blacks**
40–49	0.6	0.6	0.2	0.6
50–59	0.5	0.7	0.7	1.3
60–69	0.2	1.6	1.1	3.4
70–79	0.6	2.9	5.2	8.1
80+	7.3	8.0	14.6	18.0

Source: After Tielsch, J.M. et al., *Arch. Ophthalmol-chic.*, 108, 286, 1990.

Note: Blindness is defined as a best-corrected visual acuity of 20/200 or worse. Vision loss is defined as a best-corrected visual acuity from 20/40 to 20/200.

TABLE 13.3
Percentage of People of Different Races Classified as Blind or with Vision Loss according to the Baltimore Eye Survey with Various Causes of Blindness and Vision Loss

	Blindness		Vision Loss	
Cause	**Whites**	**Blacks**	**Whites**	**Blacks**
Cataract	13	27	38	34
Macular degeneration	30	0	22	6
Glaucoma	11	26	3	7
Diabetic retinopathy	6	5	3	11
Other retinal disorder	7	15	10	5
Optic neuropathy	2	5	3	7
Other	28	22	10	16
Unknown	4	0	13	15

Source: Sommer, A. et al., *New Engl. J. Med.*, 325, 1412, 1991; Rahmani, B. et al., *Ophthalmology*, 103, 1721, 1996.

Note: Blindness is defined as a best-corrected visual acuity of 20/200 or worse. Vision loss is defined as a best-corrected visual acuity from 20/40 to 20/200.

the percentage of people of different races classified as blind and with vision loss due to various pathological conditions. From Table 13.3, it can be seen that the most common causes of blindness and vision loss are cataract, macular degeneration, glaucoma and diabetic retinopathy, although the most common causes are different for blacks and whites. Cataract and glaucoma are the most common causes of blindness and vision loss among blacks, while macular degeneration is much more common among whites. To what extent these differences between races are caused by physiology or by differences in access to health care remains an open question.

This pattern of causal factors is typical of the developed world, after correction for any refractive errors. For vision as found, the situation globally is rather different with the major causes of vision loss or blindness being refractive error (42%) and cataract (33%). If only blindness is considered, cataract (51%) is the major cause followed by glaucoma (8%) and macular degeneration (5%) (Mariotti, 2012). The revelation that refractive error is a major cause of vision loss has lead to suggestions that the WHO classification should be revised by using visual acuity as found as a criterion, shifting the border for blindness to 20/200 (6/60) rather than 20/400 (6/120) and reclassifying low vision into two forms named moderate and mild visual impairment, these being defined by as-found visual acuity limits of 20/60 (6/18) to 20/200 (6/60) and 20/40 (6/12) to 20/60 (6/18), respectively (Dandona and Dandona, 2006). It is estimated that these changes would increase the worldwide number of people classified as blind from 37 million to 57 million and the number suffering from moderate visual impairment to 202 million from the 124 million classified as having vision loss.

It is now necessary to consider the nature of each of the more common causes of blindness and vision loss. Refractive error simply means that the image of the outside world received on the retina is out of focus. This can be readily corrected with spectacles, contact lenses or surgery. Cataract is an opacity developing in the lens. In fact, there are four main types of cataract: cortical, posterior subcapsular, nuclear and mixed, that is, some combination of the other three (Chylack, 2000). The effect of all these types of cataract is to absorb and scatter more light as it passes through the lens. This increased absorption and scattering results in reduced visual acuity and reduced contrast sensitivity over the entire visual field, as well as diminished colour discrimination and greater sensitivity to glare. The extent to which more light can help a person with cataract depends on the balance between absorption and scattering. More light will help overcome the increased absorption but if scattering is high, the consequent deterioration in the luminance contrasts in the retinal image will reduce visual capabilities.

There are two forms of macular degeneration related to age, wet and dry. Both involve deterioration of the retinal pigment epithelium under the macula. Wet macular degeneration is shown by the growth of small, leaking blood vessels into the retina. Dry macular degeneration involves the accumulation of cellular waste under the retinal pigment epithelium leading to deterioration and thinning of parts of the retina. Both wet and dry macular degeneration cause damage in and around the fovea which implies a serious decline in foveal vision, ultimately making everyday activities such as reading and seeing faces impossible. However, peripheral vision outside the macular is unaffected so the ability to orient oneself in space and to find one's way around is little changed. Providing more light, usually by way of a task light, will help people with macular deregulation (Haymes and Lee, 2006). Increasing the size of the retinal image by magnification or by getting closer is also helpful. Macular degeneration is a leading cause of blindness in the developed world and is strongly linked to age. Klein et al. (2007) found that 24% of whites of 75 years and older had early signs of macular degeneration. These early signs are strongly predictive of the later, visually catastrophic consequences of continuing macular degeneration. Unfortunately, only wet macular degeneration can be treated. Laser irradiation can be used to burn out the intruding blood vessels. Sadly, even this is of limited effectiveness, being able to do little more than slow the rate of vision loss in less than 10% of cases (Schwartz, 2000). Given the increasing number of elderly people present in the populations of developed nations, it is to be fervently hoped that some of the effort now being put into finding other treatments for macular degeneration bears fruit.

Glaucoma is best thought of as the ultimate outcome of a number of diseases that affect the eye, that outcome being progressive visual field loss (Ritch, 2000). Most forms of glaucoma follow the pattern of an event that alters the outflow from the aqueous humour, leading to elevated intraocular pressure that produces damage to the optic nerve head and hence progressive visual field loss, leading ultimately to blindness (Shields et al., 1996). As glaucoma develops, it leads to reduced contrast sensitivity, poor night vision and slowed transient adaptation, but the resolution of detail seen on-axis is unaffected until the final stage. Modifying lighting is of little value in helping people who show symptoms of glaucoma, because where damage has occurred, the retina has been destroyed. The incidence of glaucoma is strongly related to age. The treatment of glaucoma is based on reducing intraocular pressure, either by pharmaceuticals or by surgery.

Diabetic retinopathy is a consequence of chronic diabetes mellitus (Leonard and Charles, 2000). Chronic diabetes mellitus effectively destroys parts of the retina through the changes it produces in the blood vessels that supply the retina. Specifically, diabetic retinopathy is identified by the presence of microaneurysms, haemorrhages, hard exudates, changes in retinal arteries and veins and, sometimes, neovascularization. The effect these changes have on visual capabilities depends on where on the retina the haemorrhages, exudates, etc., occur and the rate at which they progress. Despite this uncertainty, the endpoint of diabetic retinopathy is clear. It is blindness. Blindness occurs 25 times more commonly in the diabetic than in the non-diabetic population (Ferris, 1993). The medical treatment of diabetic retinopathy is based on close control of blood glucose and damage control using laser photocoagulation and vitreous surgery.

To give an impression of what it is like to have one of these conditions, Figure 13.4 shows a simulation of a scene as it would appear to people with normal vision and with cataract, macular degeneration, diabetic retinopathy and glaucoma. The difficulties that must be experienced by people with any of these conditions in carrying out everyday tasks are obvious.

Although refractive error, cataract, macular degeneration, glaucoma and diabetic retinopathy have been discussed separately, it is important to appreciate that

Normal vision

Cataract

Macular degeneration

Diabetic retinopathy

Glaucoma

FIGURE 13.4 An illustration of a scene as it might appear to people with normal vision and with cataract, macular degeneration, diabetic retinopathy and glaucoma. (From the National Eye Institute, National Institutes of Health, Bethesda, MD, USA.)

having any one of them does not confer immunity to the others. In fact, the older the individual, the more likely it is that more than one of these causes of vision loss will occur. Further, treating one course of vision loss may increase the risk of another. For example, the plastic intraocular lenses used to treat cataract will transmit much more short-wavelength light to the retina than the natural lens they replace. This may be a problem because there is a possibility that exposure to short-wavelength light is associated with the development of macular degeneration (Fletcher et al., 2008) although this is a matter of controversy (Turner et al., 2010). To limit the potential damage, intraocular lenses are sometimes designed to filter out short-wavelength light. While this may protect against macular degeneration, it will have adverse consequences for vision and the circadian timing system as it will reduce the stimulation received by the rod photoreceptors and the intrinsically photosensitive retinal ganglion cells. The effects of this deficiency should be to make seeing at low light levels more difficult and to cause disrupted sleep patterns (Cuthbertson et al., 2009). As with all medical treatments, there are both benefits and side effects to be considered.

13.5 EFFECTS OF AGE ON VISUAL CAPABILITIES

As might be expected, the changes in the optical and neural characteristics of the visual system that occur with increasing age have an impact on what the visual system is capable of doing. The most likely place to find such effects is at threshold, where the visual system is operating at its limits. How significant age is in determining what the visual system is capable of is shown by a set of visual function measurements conducted by Haegerstrom-Portnoy et al. (1999). Using a sample of 900 people living in California and covering an age range of 58–102 years (mean = 75.5 years, standard deviation = 9.3 years), they measured distance visual acuity for high- and low-contrast targets at a high luminance, near visual acuity for a low-contrast target at a low luminance, contrast sensitivity, colour vision, visual field size and glare sensitivity and recovery. It is important to appreciate that all the people measured were tested as found, that is, using binocular vision with whatever spectacles or contact lenses they habitually used. This means that the sample certainly included people with various forms of vision loss and people who might have done better with up-to-date refractive correction. This makes it more representative of the population as found than samples where various classes, such as those with vision loss, are excluded. However, it cannot be completely representative as all the people tested were volunteers. Some people invited to take part in the measurements refused. These were generally older and had worse vision so the results obtained are likely to be underestimates of the effect of age on the visual function capabilities of the population.

Figure 13.5 shows the median distance visual acuity for 2-year age groups starting at 58 years, measured using a Bailey–Lovie chart (Bailey and Lovie, 1976) and expressed as the minimum angle of resolution in minutes of arc, for luminance contrasts of 0.90 and 0.17 and a background luminance of 150 cd/m^2. Clearly, there is dramatic worsening of distance visual acuity with increasing age, particularly for low-contrast stimuli.

Figure 13.6 shows the median near visual acuity for 2-year age groups starting at 58 years, measured using the dark side of a SKILL test card (Haegerstrom-Portnoy et al., 1997) and expressed as the minimum angle of resolution in minutes of arc, for a luminance contrast of 0.15 and a background luminance of 15 cd/m^2. Again, there is a worsening of visual acuity with increasing age.

Figure 13.7 shows the median contrast sensitivity for 2-year age groups measured using the Pelli–Robson chart (Pelli et al., 1988) at a luminance of 150 cd/m^2. Unlike the visual acuity measurements where the charts used show letters of a fixed luminance contrast but varying in size, the Pelli–Robson chart has large letters of a fixed size that vary in luminance contrast. Contrast sensitivity shows a steady decline with age above 58 years. Comparison of these data with those of younger people also measured using the Pelli–Robson chart shows little improvement in contrast sensitivity above that achieved by 58-year-olds (Haegerstrom-Portnoy et al., 1999).

Figure 13.8 shows the mean colour confusion score for 5-year age groups, measured on the Farnsworth Panel D-15 colour arrangement test (Farnsworth, 1947) using Commission Internationale de l'Eclairage (CIE) illuminant C to provide approximately 100 lx. For this test, males with defective colour vision were excluded. This test requires people to arrange a series of 15 discs of equal lightness and chroma but different hue into a consistent hue line, that is, into a line in which the difference in hue between adjacent discs is a minimum. Performance on the test is scored by the distance covered in colour space by a line joining the adjacent discs. The distance

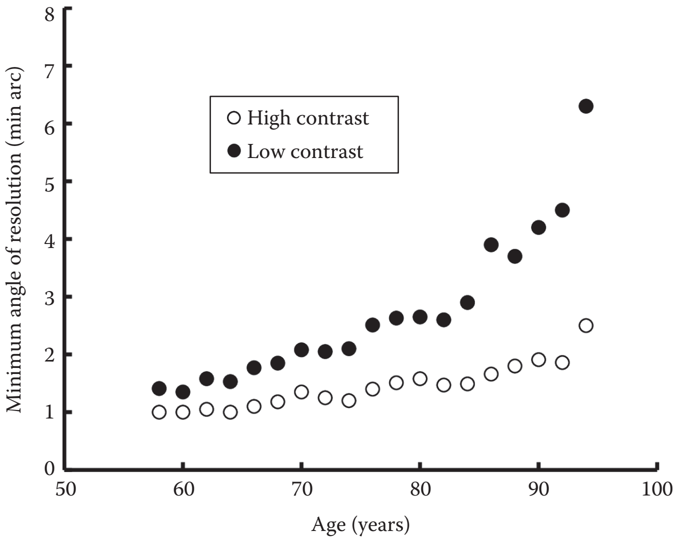


FIGURE 13.5 Median distance visual acuity for 2-year age groups, measured using a Bailey–Lovie chart and expressed as the minimum angle of resolution in minutes of arc, for high (0.90) and low (0.17) luminance contrasts at a background luminance of 150 cd/m^2. (After Haegerstrom-Portnoy, G. et al., *Optom. Vis. Sci.*, 76, 141, 1999.)

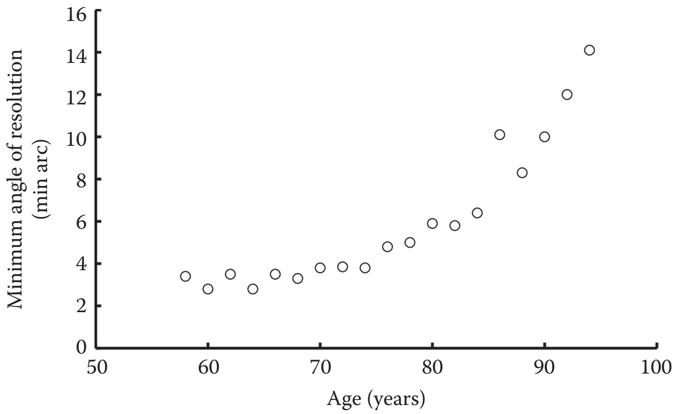


FIGURE 13.6 Median near visual acuity for 2-year age groups, measured using the dark side of a SKILL test card and expressed as the minimum angle of resolution in minutes of arc, for a luminance contrast of 0.15 and a background luminance of 15 cd/m^2. (After Haegerstrom-Portnoy, G. et al., *Optom. Vis. Sci.*, 76, 141, 1999.)

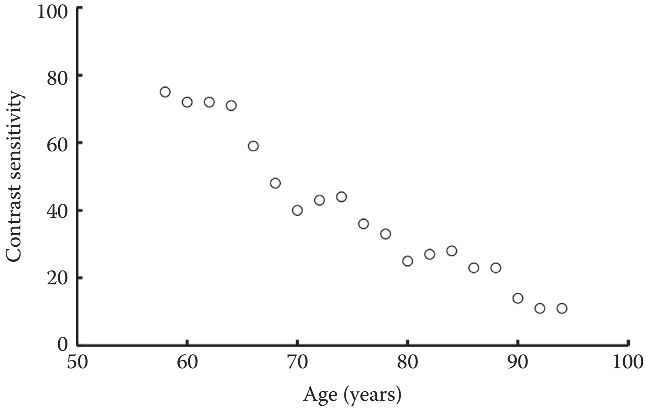


FIGURE 13.7 Median contrast sensitivity for 2-year age groups measured using the Pelli–Robson chart at a luminance of 150 cd/m². (After Haegerstrom-Portnoy, G. et al., *Optom. Vis. Sci.*, 76, 141, 1999.)

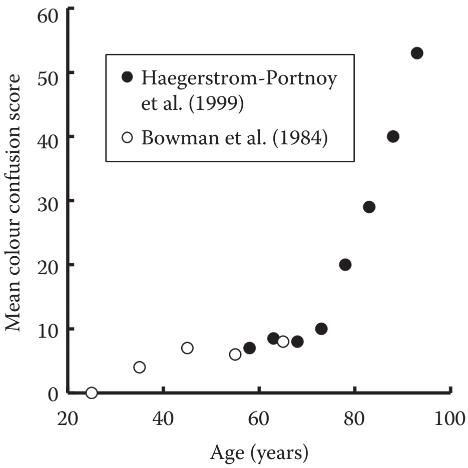


FIGURE 13.8 Mean colour confusion score for 5-year age groups, measured on the Farnsworth Panel D-15 colour arrangement test using illuminant C to provide approximately 100 lx. (After Haegerstrom-Portnoy, G. et al., *Optom. Vis. Sci.*, 76, 141, 1999.) Also shown are mean data for the same test but using younger people. (From Bowman, K.J. et al., The effect of age on performance on the panel D-15 and desaturated D-15: A quantitative evaluation, in G. Verriest, ed., *Colour Vision Deficiencies VII*, W. Junk Publishers, The Hague, the Netherlands, 1984.)

for a perfect arrangement scores zero. A distance which is twice that of a perfect arrangement scores 100. From Figure 13.8, it can be seen that the ability to discriminate colours deteriorates with increasing age. Further, the Farnsworth Panel D-15 test was designed to be insensitive to small colour differences and to identify people who had difficulties with colour discrimination in everyday life. It would seem that significant numbers of people over 75 are likely to have such problems.

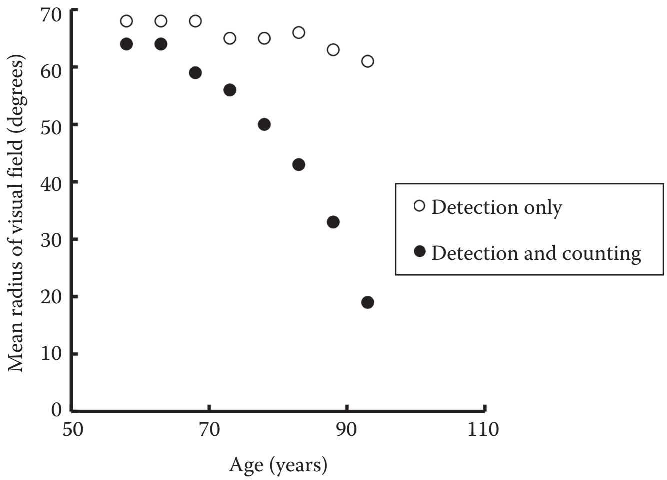


FIGURE 13.9 Mean radius of the visual field, measured in degrees, for 5-year age groups for two conditions of off-axis detection alone and with counting of flashes of the fixation point as well. The background luminance of the perimeter was 13 cd/m^2. (After Haegerstrom-Portnoy, G. et al., *Optom. Vis. Sci.*, 76, 141, 1999.)

Figure 13.9 shows the mean radius, measured in degrees, of the visual field for 5-year age groups measured using a perimeter fitted with a red light-emitting diode (LED) as a fixation point and green LEDs as targets. The background luminance of the perimeter was 13 cd/m^2. Green LED targets were presented at eight different eccentricities along five different meridians. Observers had to fixate the red LED and press a button whenever one of the green LEDs was seen to flash. The visual field radius along each meridian was defined as the most peripheral target location at which two adjacent target locations had at least 60% correct detections. A mean radius shown in Figure 13.9 is the average of the radii for the five meridians. Two viewing conditions were measured. In one, the only task was to detect the flash of a green LED while fixating the red LED. In the other, the observer had to count the number of times the red LED turned off while it was being fixated as well as detect the flash of any of the green LEDs. The difference between these two conditions is that the latter requires attention to be shared between two tasks. From Figure 13.9, it can be seen that as long as attention is directed to off-axis detection alone, the decline in visual field size with increasing age is modest but when attention is divided, the decline with age is large. This difference is due to the cognitive limits of old age rather than any changes in vision.

Figure 13.10 shows the median number of letters lost due to disability glare for 2-year age groups. The test used to quantify the effect of disability glare was the Berkeley Glare Test (Bailey and Bullimore, 1991). This consists of a small opaque triangular letter chart illuminated from the front to 80 cd/m^2 and surrounded by a translucent panel with a luminance of 3300 cd/m^2 acting as a glare source. The letters on the chart are of low-luminance contrast (0.10). The difference between the number of letters correctly read with and without the glare source is the number

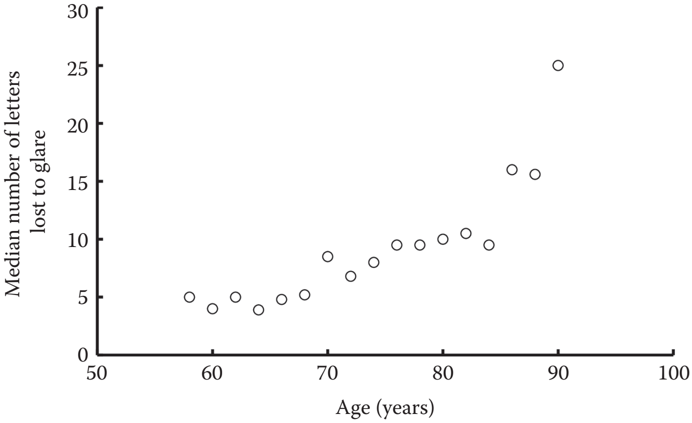


FIGURE 13.10 Median number of letters lost from the Berkeley Glare Test due to disability glare for 2-year age groups. (After Haegerstrom-Portnoy, G. et al., *Optom. Vis. Sci.*, 76, 141, 1999.)

of letters lost. As can be seen from Figure 13.10, there is an almost exponential increase in number of letters lost with increasing age above 60 years of age. This is to be expected given the increase in light absorption and scatter in the eye in old age. Appropriately, Vos (1995) and CIE (2002b) provide a modification of the disability glare formula to account for age (see Section 5.4.2.1 for the unmodified disability glare formula). The modified formula is

$$L_v = 10\left[1 + \left(\frac{A}{70}\right)^4\right]\sum\left(E_n\theta_n^{-2}\right)$$

where

L_v is the equivalent veiling luminance (cd/m^2)

A is the age (years)

E_n is the illuminance at the eye from the nth glare source (lx)

θ_n is the angle between the line of sight and the nth glare source (degrees)

This formula implies that equivalent veiling luminance increases with age.

Figure 13.11 shows the median time taken to recover from exposure to glare for 5-year age groups. The SKILL near acuity test (Haegerstrom-Portnoy et al., 1997) was used at a luminance contrast of 0.15 and with a background luminance of 15 cd/m^2. The observer was required to look directly at the Berkeley Glare Test glare source of luminance 3300 cd/m^2 for 1 min. The glare source was then turned off and the time taken for the observer to reach a level of visual acuity two lines better than their individual threshold measured without glare was recorded. Figure 13.11 shows that glare recovery times increase dramatically with age.

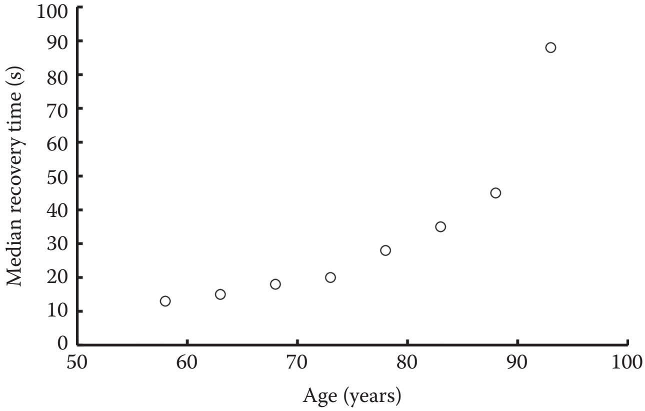


FIGURE 13.11 Median time taken, in seconds, to recover visual acuity following 1 min exposure to a glare source of 3300 cd/m^2 luminance for 5-year age groups. The SKILL near acuity test was used at a luminance contrast of 0.15 with a background luminance of 15 cd/m^2. (After Haegerstrom-Portnoy, G. et al., *Optom. Vis. Sci.*, 76, 141, 1999.)

By now, it should be obvious that there is a general deterioration in many visual functions in old age, but it is important to note that there are also wide individual differences, the range of individual differences increasing as age increases (Johnson and Choy, 1987; Haegerstrom-Portnoy et al., 1999). It is also important to appreciate that there are a few aspects of visual function that change little with normal aging. Specifically, vernier acuity, the ability to detect whether two lines are directly in line or are offset relative to each other, does not deteriorate with age (Enoch et al., 1995), and neither do several aspects of colour vision, such as the wavelength of unique hues (Werner and Kraft, 1995). The thing these two very different aspects of vision have in common, and what differentiates them from many other measures of visual function, is that they are the result of neural data processing of difference signals, and difference signals are not sensitive to changes that affect both parts of the signal equally.

The changes in visual function with age shown in Figures 13.5 through 13.11 inclusive were obtained from a sample of people representative of the population at each age, including those with vision loss. Of course, people with vision loss can be expected to show much worse threshold performance than people of the same age with normal sight. Indeed, as discussed in Section 13.4, a markedly poorer visual acuity is one of the criteria for classifying someone as having vision loss. How dramatic the decline in threshold performance can be is shown in Figure 13.12 (Paulsson and Sjostrand, 1980). This shows the threshold contrast for a grating of different spatial frequencies, for two people, one with and the other without a cataract, with and without a high-luminance surround. Clearly, the presence of a cataract increases threshold contrast even in the absence of a high-luminance surround, but when the bright surround is introduced, the difference between the two people increases greatly, because the light from the high-luminance surround is scattered by the cataract over the part of the retinal image containing the threshold contrast target.

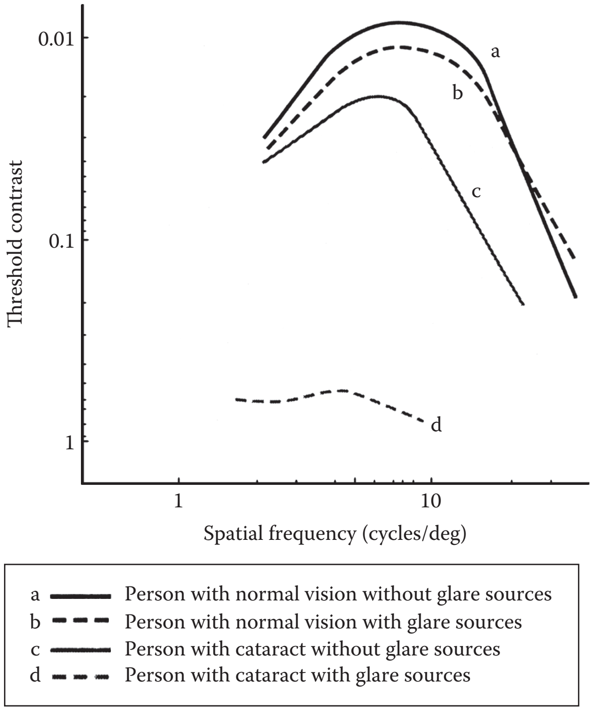


FIGURE 13.12 Threshold contrast plotted against spatial frequency for two people, one with normal vision and the other with cataract, with and without a glare sources present. (After Paulsson, L. and Sjostrand, J., *Invest. Ophthalmol. Vis. Sci.*, 19, 401, 1980.)

13.6 EFFECTS OF AGE ON REAL VISUAL TASKS

The worsening in such threshold measures as visual acuity, contrast sensitivity, colour discrimination, visual field size and glare sensitivity and recovery with age has implications for the performance of many real tasks. Kosnik et al. (1988) confirmed this in survey of several hundred people ranging from 18 to 100 years of age. The purpose of the surveys was to determine what visual problems the people experienced in daily life. Five types of visual problems that increased in difficulty with age were identified. They were seeing in dim light, reading small print, distinguishing dark colours, reading moving information and visual search. These problems can be divided into two types: those where the information sought is of one type and the position where it may be found is known, for example, reading, and those where many different types of information are needed but where they may be found is unclear, for example, driving.

Whittaker and Lovie-Kitchin (1993) reviewed the literature on reading rate and found that there were four factors that were important for improving the reading rate. The four factors were acuity reserve (print size relative to threshold visual acuity), contrast reserve (luminance contrast of print relative to threshold contrast), number of letters visible and size of central field loss. Clearly, if visual acuity and threshold contrast worsen with age or vision loss, then the acuity reserve and the contrast reserve are less, so reading rate will decrease. In general, the closer the stimulus provided by a task is to the threshold of the observer for that stimulus, the worse the task performance will be although, as discussed in Section 4.3.5, the relationship between task performance and visual stimuli is not a simple linear function. Rather, the importance of vision to the change in task performance with age, for a specific task, depends on two factors: the role of the visual component in the task and how close to threshold the visual stimuli presented by the task are. If the visual component is insignificant, then the change in task performance will be slight, even if visual capabilities are much diminished. If the task is dominated by vision, then the changes in vision that occur with age will have an important effect on task performance. As for the proximity to threshold, the 'plateau and escarpment' shape of visual performance (Boyce and Rea, 1987) implies that the effects of age on visual performance will be much more marked for tasks where the visual stimuli are close to threshold than when they are far above threshold. For example, Bailey et al. (1993) showed that reading speed improved as the acuity reserve increased, until the print size was about four times as big as the threshold size, after which no further improvement occurred.

As for driving, Wood (2002) measured the performance of groups of drivers of different ages and with different degrees of vision loss. Specifically, 139 drivers in good general health and holding a current Queensland, Australia, driving license were divided into five groups, labelled young, middle-aged and old, this last group being subdivided into those with normal vision, mild vision loss and moderate or severe vision loss. The mean ages of the three age groups were 27, 52 and 70 years for the young, middle-aged and old groups, respectively. For the old group with normal vision, mild vision loss and moderate vision loss, the mean ages were 69, 71 and 71 years, respectively. Normal vision was defined as having a visual acuity of 20/25 (6/7.5) or better. Mild vision loss was defined as having slight clouding of the lens, early glaucoma or early macular degeneration in one or both eyes. Moderate to severe vision loss was defined as having cataract in both eyes or advanced glaucoma or macular degeneration in one or both eyes. All these drivers drove round a 5.1 km (3.2 miles), road circuit closed to the public and hence which was free of other traffic. While driving round the circuit, the drivers were asked to report any road signs they saw; to report any large low-contrast hazards they saw in the road and to avoid them by steering around them; to judge whether or not the gap between a pair of cones was wide enough to get through and, if it was, to drive through it and, if it was not, to drive around it; and to respond to the onset of one of the five LEDs mounted in the car in front of the driver. Having driven round the circuit, the drivers' ability to handle the vehicle was tested by having them manoeuvre it in and out of a row of low-contrast cones and reverse into a parking space. Table 13.4 gives the measures of driving performance that showed statistically significant differences between the groups. As would be expected, both age and vision loss tend to produce worse driving performance but the balance between these two factors changes with the nature of the task. For tasks that involve switching attention, such as detecting the onset of the LED stimulus, age is the dominant factor. For tasks where visibility is limited, such as the detecting and avoiding low-contrast road hazards, vision loss is more important. For other tasks, such as reversing, both age and vision loss are influential.

TABLE 13.4
Mean Performance Measures for Young, Middle-Aged and Old Drivers, the Old Drivers Being Divided into Those with Normal Vision, Mild Vision Loss or Moderate or Severe Vision Loss

Driving Performance Measure	Maximum Possible	Young Drivers	Middle-Aged Drivers	Old Drivers with Normal Vision	Old Drivers with Mild Vision Loss	Old Drivers with Moderate or Severe Vision Loss
Road signs seen	65	51.3	50.0	46.4	46.9	40.7
Road hazards seen	9	8.7	8.7	8.7	8.4	8.0
Road hazards hit	9	0.3	0.3	0.5	0.6	1.8
Number of LEDs seen	15	11.5	10.2	7.3	8.2	7.8
Correct gap manoeuvres	9	8.0	7.7	7.3	7.2	6.5
Cones hit while manoeuvring	9	0.5	0.2	0.3	0.7	0.4
Circuit time (s)	—	428	434	468	482	478
Manoeuvre time (s)	—	38.1	38.7	41.5	49.1	48.8
Reversing time (s)	—	30.9	39.0	48.5	62.6	62.8

Source: After Wood, J.M., *Hum. Factors*, 44, 482, 2002.
Note: These measures were obtained on a closed road circuit.

Given that visual function declines with age until, for many people, vision loss occurs, it is interesting to consider what forms of visual function are of most importance for driving. Owsley and McGwin Jr. (2010) have reviewed the relationship between visual function and two aspects of driving: performance and safety. Driving performance is usually measured by the ability to control the vehicle around a real or simulated course (Wood, 2002). Driver safety is measured by the involvement in collisions on the road (Rubin et al., 2007). Curiously, the visual function that is most widely used to assess suitability for driving, visual acuity, is very weakly associated with safety and only linked to driver performance for those tasks that require resolution of detail, such as recognizing road signs. More important for driver performance are the changes with age that lead to reduced contrast sensitivity, visual field loss and longer visual processing speeds, particularly when attention has to be divided. Of these three visual functions, only the last has been shown to be reliably related to driver safety (Owsley et al., 1998). This divergence between driver performance and safety can probably be explained by the fact that older drivers are often aware of their limitations and some modify their behaviour accordingly, for example, by avoiding driving at night or only using routes they are familiar with.

This discussion of the changes in visual function with age on two real and important tasks, reading and driving, emphasizes the need to carry out an analysis of the task to determine what aspects of vision are used in doing the task and to assess the relative importance of the visual and cognitive components. For reading in a familiar language and vocabulary, the visual component is dominant and the visual functions that matter are those that affect the on-axis perception of detail. In turn, this suggests that lighting conditions are going to be important for quick and accurate reading. For driving, the apparent importance of the speed of processing visual information for driver performance and driver safety suggests that the cognitive component is dominant. It might be thought that this implies that lighting conditions are not important for driving but that is not the case. If it takes an elderly driver longer to process all the visual information presented to him, lighting has a vital role to play in making sure that significant information is highly visible. It also makes a case for good road lighting where there is an aging population of drivers. Good road lighting ensures that the road ahead and vehicles and objects on and near it are visible at a much greater distance than is possible with headlamps alone (see Section 10.4.4). This gives the driver more time to process the information received.

13.7 EFFECTS OF AGE ON THE CIRCADIAN TIMING SYSTEM

With increasing age, the amplitude of the circadian timing rhythm diminishes (Brock, 1991; Copinschi and van Cauter, 1995), the period shortens, and the phase advances (Renfrew et al., 1987; Czeisler et al., 1988a). The overall effect is to diminish the ability to synchronize this circadian rhythm to the external environment with consequences for many basic physiological functions (Turner et al., 2010). In the absence of clear signals from the suprachiasmatic nuclei, various organs of the body can become uncoordinated resulting in biochemical confusion. This confusion can become evident in both the short and long term. Short-term disruption of the circadian rhythm leads to declines in alertness, cognitive functioning, mood and sleep problems (Turner et al., 2010). Long-term disruption of the circadian rhythm is associated with cardiovascular disease and early death (Knutsson et al., 2004). Lighting has a role to play in avoiding these consequences of circadian disruption (see Section 14.4).

13.8 WHAT CAN BE DONE TO OFFSET THE EFFECTS OF AGE?

Given that both the visual and the circadian timing systems deteriorate with age, what can be done to offset the effects of these changes? For vision, there are four possible approaches. They are to change the optics of the eye so as to provide a sharp retinal image of the task, change the task so that the stimuli it presents are further from threshold, change the lighting to enhance the capabilities of the visual system or to move the stimuli presented by the task further from threshold and to eliminate the need to do the task at all. Each will be discussed in turn. For circadian timing, the possibilities are more limited, basically consisting of increasing the stimulus to the intrinsically photosensitive retinal ganglion cells by increasing exposure to short-wavelength light at appropriate times and for suitable durations.

13.8.1 Changing the Optics

The first and most widely experienced effect of aging on the visual system is the recession of the near point caused by the increased rigidity of the lens. Eventually, the near point moves so far away that it is no longer possible to bring an object positioned at a normal distance to focus on the retina, for example, it is no longer possible to read a newspaper, even when held at arm's length. This problem can be overcome by the use of spectacles or contact lenses with the appropriate optical power. Figure 13.13 shows the effect of correcting for refraction errors by wearing spectacles on visual acuity, for near and distant vision, for people of different ages. Wearing spectacles to bring the retinal image into focus produces a marked improvement in visual acuity for older people, although it does not completely restore visual acuity to what it was when young because simply wearing spectacles does nothing to offset the other optical and neural changes that occur in the eye with age.

The other reason why the optics of the eye are sometimes changed, a change that is becoming much more common in the elderly, is the development of cataract. Today, it is routine to replace a brunescent lens with a plastic lens. It might be thought that removing a cataract and substituting a clear, intraocular lens has the potential to make the retinal image better than it was before the onset of the cataract, but this is not always so. Whether it does or not depends on the way in which the lens is removed and the optical characteristics of the intraocular lens (Nadler, 1990). Removing a cataract certainly reduces light absorption, light scatter and lens fluorescence but may introduce new sources of light scatter and will do nothing for any neural degradation that has occurred. Nonetheless, for many people, removing a cataract will markedly improve visual acuity, contrast sensitivity and colour vision as well as reduce disability glare (Rubin et al., 1993).

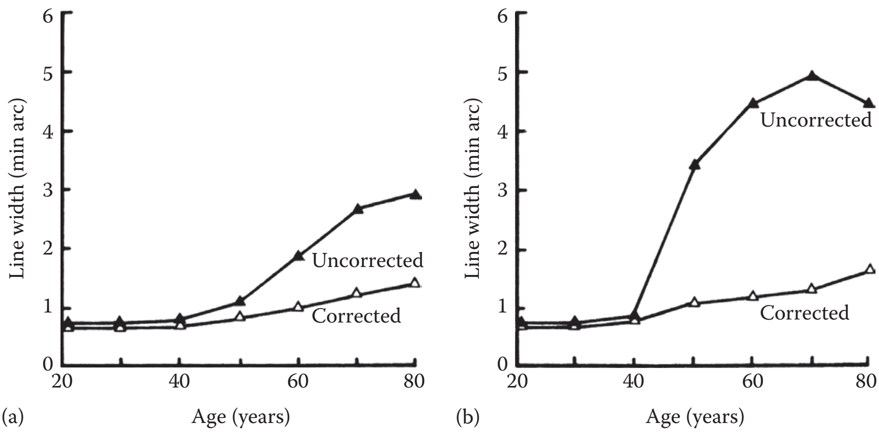


FIGURE 13.13 Subtended line widths of letters that can just be read by 50% of observers, for (a) distant and (b) near vision, with and without their usual spectacles, plotted against age. For distant vision, the test letters were 6 m from the observer while for near vision, they were 0.36 m from the observer. (After United States Department of Health, Education and Welfare [USDHEW], *Binocular Visual Acuity of Adults – US 1960–1962*, USDHEW, Washington, DC, 1964.)

As for the circadian timing system, Asplund and Lindblad (2002, 2004) have shown that cataract surgery leads to an improvement in sleep at night and reduces sleepiness during the day. Such effects are what would be expected to follow from an increase in the amount of short-wavelength light reaching the retina.

13.8.2 Changing the Task

Another approach to offsetting the effects of age on task performance is to change the visual stimuli presented by the task. The relative visual performance (RVP) model of visual performance (see Section 4.3.5) demonstrates that increasing the size or contrast of the task, and hence moving the task further from threshold, produces an improvement in visual performance for young people with normal vision. It is reasonable to assume that increasing size will have an even greater beneficial effect for the elderly and for people with vision loss. Figure 13.14 shows the speed and accuracy of doing a high-contrast Landolt ring task (see Figure 4.4) with rings of different sizes, for two age groups, one 18–28 years and the other 61–78 years (Boyce et al., 2003b). Speed is measured as the number of Landolt rings examined in 20 s. Accuracy is measured as the number of Landolt rings of a specified gap orientation found as a percentage of the actual number of Landolt rings with the specified gap orientation examined in 20 s. As would be expected, Figure 13.14 shows that increasing the size of the gap in the Landolt ring leads to greater speed and higher accuracy until saturation occurs. This is true for both age groups. However, the effects of increasing size are more marked for the older age group, particularly for accuracy when the gap size is small. This is because the smallest gap size is closer to threshold for the older age group, 9 of the 38 older participants being unable to do the task at the smallest size. Figure 13.14 also shows that enhancing the visual stimulus will not bring the level of performance of the older subjects to that of the young subjects. Even at the largest gap size, there is a difference in both speed and accuracy of performance between the two age groups. This is because increasing the size of the visual stimulus does nothing to address the optical and neural changes in the eye and the general slowing of cognitive function that occur with advanced years.

The size of the retinal image of a task can be increased either by making the task bigger, for example, large print books, or by bringing the task closer, although this may be limited by the need to keep the resulting image in focus on the retina, or by using some form of magnification. Magnification can be achieved either optically or electronically, but both forms need to be optimized for the individual and the task. This is because the greater is the magnification, the smaller is the field of view. If the task involves some form of scanning, for example, reading text, then optimization of the magnification and field of view is essential. Legge et al. (1985a) found that for people with normal vision, reading rate decreased once the angle subtended by the character width exceeded 2°.

One situation where magnification might be thought to be of great value is for people who have lost foveal vision, for example, people with macular degeneration. Unfortunately, the benefit of magnification is not as great as expected. Legge et al. (1985b) found that even with a very large character size, people who had lost their central vision could never read at a rate of greater than 70 words/min, whereas

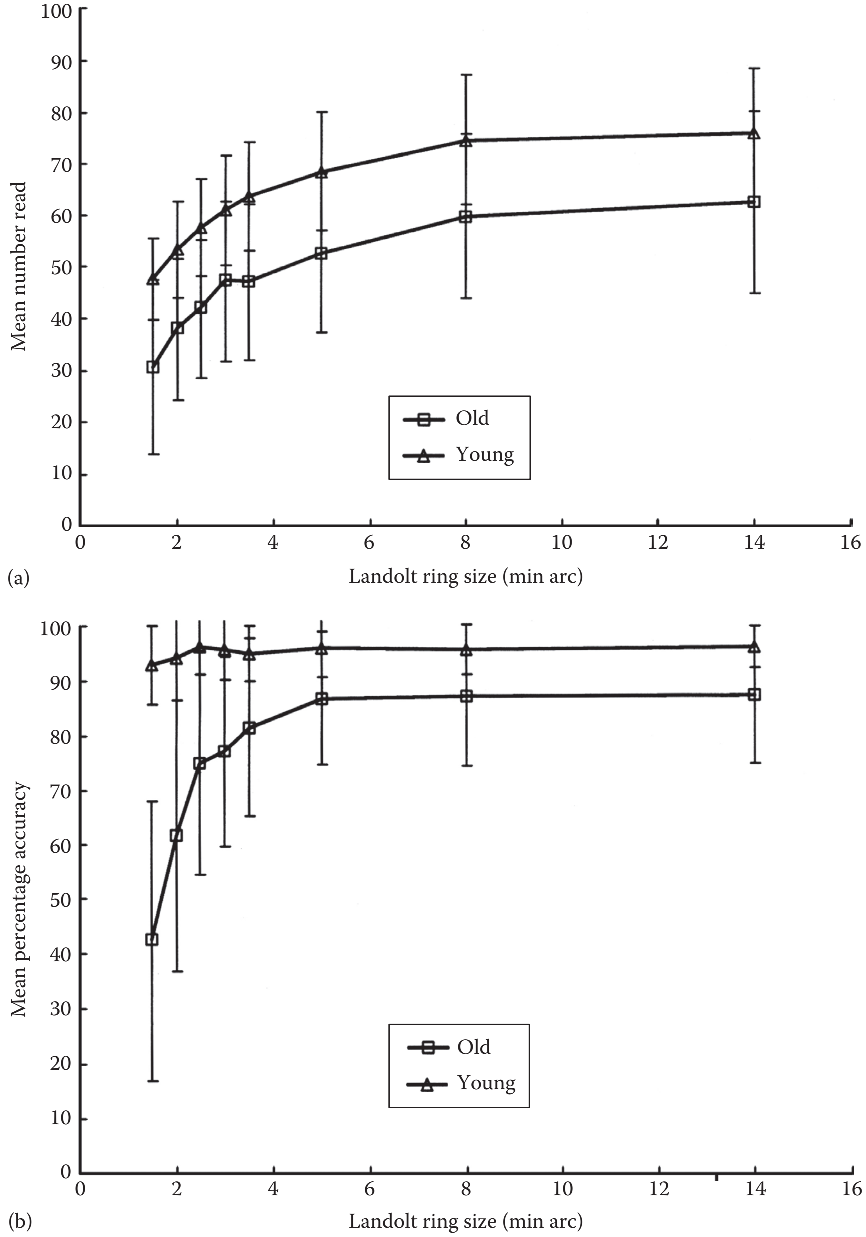


FIGURE 13.14 (a) Speed and (b) accuracy of performance of a high-contrast Landolt ring task, plotted against Landolt ring gap size measured in angular subtense at the eye, for two age groups (18–28 and 61–78 years). Speed is measured as the mean number of Landolt rings examined in 20 s. Accuracy is measured as the mean number of Landolt rings of a specified gap orientation found as a percentage of the number of Landolt rings with the specified gap orientation examined, in 20 s. The error bars are standard deviations. (After Boyce, P.R. et al., *Lighting Res. Technol*., 35, 141, 2003b.)

people with intact foveal vision could approach reading rates of 200–300 words/min. The improvement that does occur with magnification occurs because the effect is to enlarge the retinal image so that it extends over the near periphery of the retina, an area that is unaffected by macular degeneration. Unfortunately, visual acuity decreases with retinal eccentricity (Westheimer, 1987).

Size is just one dimension that can be used to make a task easier to do. Another is luminance contrast. Again, the RVP model of visual performance (see Section 4.3.5) shows that increasing luminance contrast will lead to better visual performance for young people. It is reasonable to assume that increasing luminance contrast will have even greater beneficial effects for the elderly and for people with vision loss. Certainly, the idea of increasing luminance contrast is a feature of much advice on how to make life easier for people with vision loss. For example, Sicurella (1977) recommends that people with vision loss should have a sheet of black paper and a sheet of white paper on the kitchen wall. Then, the level of either a light or a dark liquid in a transparent container can be more easily seen by viewing the container against the opposite background. A similar approach can be used to allow people with cataract and other forms of vision loss that result in a blurry retinal image to orientate themselves in a space. Specifically, a high-luminance contrast between floor and walls, between walls and door and between door and door handle will help such a person find the door and open it. While high-luminance contrasts of this type are undoubtedly useful, they should be attached only to salient aspects of the space. To enhance safe and confident movement about a space, the ideal to aim for is to create the impression of a line drawing of the scene, in which the high-luminance contrast between salient parts of the scene represents the lines of the drawing. Too many different luminance contrasts produce a confusing picture for people with vision loss to interpret.

Another factor that needs to be considered when seeking to maximize luminance contrast is the amount of scattered light produced in the eye. Scattered light will tend to reduce luminance contrast of the retinal image of the task. One simple means to reduce the amount of scatter is to reduce the luminance of the area immediately surrounding the task. Legge et al. (1985b) found that people with cataract and other conditions that would lead to a large amount of scattered light could read white letters against a black background much more easily than black letters against a white background. The reduction in scattered light from the background is what lies behind a device widely used by those with cataract to make reading easier. The device is a piece of black card with a slot cut in it. The slot is positioned over the page so that only one or two lines of print can be seen at a time. The low luminance of the background to the print minimizes the reduction of the luminance contrast of the print by scattered light.

There are several different means to reduce scattered light and stray light from a much larger visual field. These range from the wearing of an opaque visor or cap, which shields the eyes from the sun and sky outdoors and luminaires overhead indoors, to the wearing of photochromic, polarizing, spectrally selective sunglasses. Daylight outdoors can vary greatly in amount, is polarized, and constitutes the most common source of exposure to high-intensity ultraviolet radiation. The photochromic component of the sunglasses adjusts the transmittance of the glasses according to the amount of light available. The polarizing component removes vertically polarized light, which is produced as highlights after reflection from water and other specularly reflecting surfaces. These highlights reduce the luminance contrast of the object in two ways: at the object itself and by scattered light in the eye. Finally, the sunglasses are designed to transmit little light at wavelengths below about 550 nm. Thus, they cut out most of the incident radiation that generates lens fluorescence and increase the luminance contrast between surfaces that are predominantly blue or green relative to those that are predominantly yellow or red. Glasses that stop short-wavelength radiation from reaching the eye have been shown to improve the vision of people with cataracts and macular degeneration (Tupper et al., 1985; Rutkowsky, 1987; Zigman, 1992).

Another dimension that might be used to enhance visual performance is surface colour. Colour can be used to enhance visual performance in three different ways. The first is to identify objects. Wurm et al. (1993) found that colour does improve the recognition of images of familiar foods by people with normal vision and vision loss. The second is to make items more conspicuous which improves visual search (see Section 8.5). The third is as a substitute for luminance contrast. In the absence of luminance contrast, a colour difference between the task and its immediate background is the only way in which the task can be seen. However, this is a rather extreme situation. Colour difference only becomes important when the luminance contrast is low (see Section 4.3.6). When luminance contrast is high, there is little to be gained in terms of visibility by enhancing colour difference as shown by the fact that adding colour to text produces no significant improvement in reading speed (Knoblauch et al., 1991).

Finally, where what has to be seen can be presented on a self-luminous display, there is the possibility of using image enhancement to help people with vision loss. Peli and Peli (1984) suggest using an adaptive image enhancement technique in which the image is processed one pixel at a time based on its local characteristics. Specifically, the image is divided into its low and high spatial frequency components, which is analogous to the local contrast. The high-frequency components are amplified while the low-frequency components are shifted towards the mid-range. The effect is to enhance the contrast and sharpness of the elements of the image and hence make its details more visible.

13.8.3 Changing the Lighting

The characteristics of lighting that can produce an improvement in visual performance are the amount of light, the spectrum of the light and the spatial distribution of light. Each will be considered in turn.

The RVP model of visual performance (see Section 4.3.5) demonstrates that increasing the retinal illuminance will lead to an improvement in visual performance, although the magnitude of the improvement will vary with the separation of the size and contrast of the task from their respective threshold values: the greater the separation, the less the impact of increasing the retinal illuminance. The effect of age up to 65 years is taken into account in the RVP model by adjusting the retinal illuminance for the decreased pupil size and the increased absorption of light in the eye that occurs with age and by adjusting threshold contrast for light scattered in the eye (Rea and Ouellette, 1991).

Unfortunately, there is neither an equivalent to the RVP model for people with vision loss nor, given the large individual differences, is there ever likely to be. What can be said is that any vision loss that is characterized by a reduction in the retinal illumination without a reduction in the clarity of the retinal image is likely to benefit from increased illuminance. This view is supported by the observations of Sloan et al. (1973), who measured the ability of people with macular degeneration to read under normal room lighting and under a high-intensity reading lamp. With the reading lamp, many of the patients were able to read continuous text without magnification or with much less magnification than was required under the normal room lighting. Eldred (1992) also reports faster reading speeds at dramatically higher illuminances by people with macular degeneration. Cornelissen et al. (1995) examined object perception in a simulated living room lit to illuminances in the range 1.6–5000 lx. All the objects could be recognized by people with normal vision at 1.6 lx. All the participants, who had several different forms of vision loss, showed improvement in their ability to detect and recognize the objects as the illuminance was increased although there were considerable differences among them with respect to whether, and at what illuminance, the improvement ceased. Similarly, Evans et al. (2010) measured the performance of people with cataract or macular degeneration on four everyday tasks: walking along a corridor with ramps, inserting a plug into a socket, sorting pills and reading, all at 50, 200 and 800 lx. They found that while performance generally improved with higher illuminances, there were very large individual differences, so much so that they concluded that the best approach to identifying the optimal lighting conditions for people with vision loss was to carry out individual assessments of their performance and preference. Others have argued that this is an example of the best being the enemy of the good and that there are a number of rules of thumb that can be usefully employed when designing lighting for people with vision loss (Brodrick and Barrett, 2008). Both opinions are right, the difference between them being a matter of practicality rather than veracity. Certainly, there is no shortage of simple advice aimed at people with vision loss on how to improve the lighting of their homes (RNIB and Thomas Pocklington Trust, 2009).

So far, this discussion of the benefits of increased illuminance for those with sight loss has been qualitative. In an attempt to be quantitative, Lindner et al. (1989) measured the preferred illuminance to read high-contrast printing. Each participant could adjust the illuminance provided by a large array of ceiling-mounted fluorescent lamps over a wide range using a continuously variable dimming system. Table 13.5 shows the median illuminance selected and the 10th and 90th percentiles of groups of people with normal (emmetropic) vision and various types of vision loss, for three types of fluorescent lamp. Again, the most obvious feature of these results is the magnitude of the individual differences in preferred illuminance, within each group. The next most obvious feature is unexpected. It is that the median illuminances preferred by the young emmetropic group are much higher than for any other group. Given the clearer optic media of the younger

TABLE 13.5
Median Preferred Illuminance and the 10th and 90th Percentiles for Reading High-Contrast Printing of Line Width Subtending 4.4 min Arc at 30 cm, under Three Different Types of Fluorescent Lamp

State of Vision	Number of Subjects	Fluorescent Lamp Type	Median Preferred Illuminance (lx)	10th and 90th Percentile of Illuminance (lx)
Emmetropic 20–30 years	50	White	900	329–2072
		Warm-white	1000	600–2127
		Daylight	1055	426–2090
Emmetropic 40–79 years	50	White	268	75–817
		Warm-white	260	105–1527
		Daylight	315	162–1753
Cataract – preoperative 40–80 years	75	White	325	98–1800
		Warm-white	300	45–1496
		Daylight	448	52–1450
Cataract – post-operative with intraocular lens	50	White	121	70–1162
		Warm-white	123	50–939
		Daylight	140	60–1197
Cataract – post-operative with spectacle correction	25	White	119	75–439
		Warm-white	128	39–629
		Daylight	195	54–656
Glaucoma 40–82 years	50	White	596	100–1071
		Warm-white	480	85–1278
		Daylight	675	67–1866

Source: Lindner, H. et al., *Lighting Res. Technol.*, 21, 1, 1989.

group, it might be expected that they would prefer a lower illuminance than the others. The fact is they do not. This could be a matter of expectation based on the younger group's exposure to higher illuminances or simply because the older people in the other groups disliked higher illuminances because of the greater amount of scattered light and stray light produced in the eye. Three other aspects of these results deserve mention. The first is the tendency for preoperative cataract patients to choose lower illuminances than glaucoma patients. This is to be expected because of the greater scattering of light in the eyes of cataract patients. The second is the reduction in illuminance preferred by post-operative cataract patients. This is to be expected because of the increased light transmittance and reduced light absorption and scattering that occurs when the brunescent lens is replaced with a clear plastic lens. The third is the relatively small difference among the types of fluorescent lamp. This indicates that small differences in the lamp spectrum are unimportant.

One other effect of increasing the retinal illuminance is to improve the ability to discriminate colours. Figure 13.15 shows the effect of increased age and illuminance

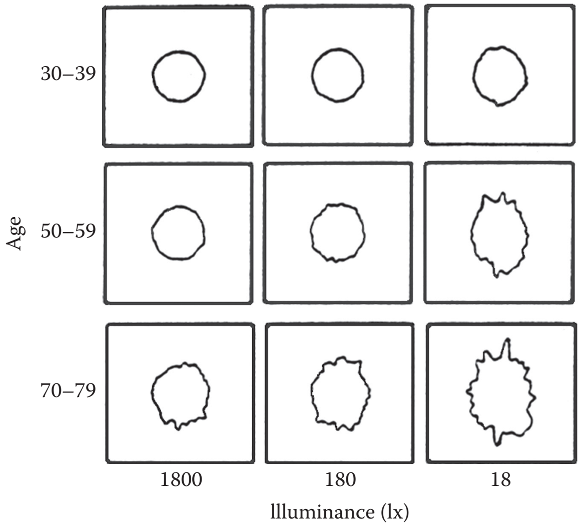


FIGURE 13.15 The average distribution of errors on the Farnsworth–Munsell 100 hue test as function of illuminance and age. (After Knoblauch, K. et al., *Appl. Opt.*, 26, 1441, 1987.)

on the ability of people of different ages to discriminate the hue samples forming the Farnsworth–Munsell 100 hue test (Knoblauch et al., 1987). The Farnsworth–Munsell 100 hue test is a test of hue discrimination that requires the subject to arrange a series of 85 coloured discs of equal lightness and chroma but different hue into a consistent hue circle, that is, into a circle in which the difference in hue between adjacent discs is a minimum. Performance on the test is scored by the magnitude of the misplacements of discs on the circle. In Figure 13.15, zero error is indicated by a smooth circle. As the number of errors increases, the circle becomes larger and more ragged. The distance from the centre point in a given radial direction is a measure of the magnitude of the error in hue discrimination made for the particular hue represented by the radial direction. Examination of Figure 13.15 suggests that older people tend to make more errors in hue discrimination, particularly at low illuminances. It is clear that increasing the retinal illuminance enables finer hue discriminations to be made by older people.

An alternative approach to enhancing the discrimination of colours is to change the light spectrum forming the illumination. It is much easier to discriminate colours that are widely separated in colour space than those that are close together. The extent to which a light source will separate colours in colour space is correlated to its gamut area. Thus, the simplest advice for lighting places used by elderly people would be to use only lamps with a large gamut area, although if colours are to have the expected appearance, the light source should also have a high CIE general colour rendering index (see Section 1.6.3.2).

Another aspect of lighting that can be important in determining the ability of the elderly and those with vision loss to function is the distribution of light. This can be considered in two locations: the surrounding space, either interior or exterior, and the task. In both cases, it is desirable that the light be uniformly distributed on all the relevant surfaces, without casting shadows (Julian, 1983). In a room, the primary factors that determine the illuminance uniformity of a lighting installation are the luminous intensity distribution of the luminaires, the spacing between luminaires and the reflectances of the room surfaces. Different luminaires can have very different luminous intensity distributions, so if the aim is to achieve uniform lighting, the selection of an appropriate luminaire is important. Indirect luminaires are particularly effective in producing uniform lighting without shadows. Also, where uniform lighting is required, the maximum spacing between luminaires recommended by the manufacturer and based on the luminaire's luminous intensity distribution should not be exceeded. As for surface reflectances, a uniform distribution of light is much easier to achieve when the room surface reflectances are high rather than low. Similar considerations apply to exteriors, although there the role of surface reflectance may be limited. Maintaining a uniform illuminance distribution is particularly important for people with vision loss because of the problems they face at low light levels and because they may have difficulty in discriminating between a pattern of illuminance and a pattern of reflectance. Such conflicting patterns are likely to cause confusion, particularly where the pattern of illuminance differences produces higher luminance contrasts than the pattern of reflectances.

The distribution of light in the immediate task area is also important. Sanford (1996) examined the trade-off between the illuminance and the area illuminated for a group of people with macular degeneration, doing a reading task. The higher illuminance was preferred until the boundary of the area illuminated fell within the boundary of the area to be read. This is another example of the illuminance pattern conflicting with the reflectance pattern, and it emphasizes the desirability of uniformly lighting the area containing the task.

Light distribution is particularly important when self-luminous displays, such as television screens and computer monitors, are being used. The lighting in a room makes self-luminous displays less visible in two ways. First, ambient light reflected from the screen reduces the luminance contrast and desaturates the colours of the display. Second, when the screen is specular, light reflected from the front surface of the screen produces an image of the room, the screen acting as a low-reflectance mirror (Boyce, 1991; Lloyd et al., 1996). If the room contains high-luminance luminaires or windows, two alternative views of the world can be seen: one generated by the display and the other by the specular reflection. Again, separating these two views of the world will be difficult for people with vision loss. In a small space, such as a private office or at home, reflections from the screen can be avoided by careful positioning. In large spaces containing many screens, luminaires specifically designed for use in such spaces, with restricted luminous intensity distributions, should be used (see Section 7.4.2.3).

An adverse aspect of light distribution that sometimes occurs is glare. Glare can take several forms (Vos, 2003). The two forms of concern here are discomfort and disability glare. The increased scattering of light in the eye that occurs with increasing age can be expected to produce increases in the level of disability glare produced by a given lighting installation. Disability glare is caused primarily by light scattered in the eye (Vos, 1984). The formula for predicting the magnitude of disability glare and the way it has been modified for the observer's age has been discussed in Section 13.5. The extent to which disability glare reduces visual function depends on the luminance contrast of what is to be seen, its angular deviation from the glare source and the luminance of the rest of the visual field. Elderly people generally have more light scatter and hence experience greater disability glare than the young, and people with such causes of vision loss as cataract have even more (Storch and Bodis-Wollner, 1990; de Waard et al., 1992). The formula for disability glare shows that the greater is the deviation of the glare source from the line of sight, the less is the magnitude of disability glare. The luminance contrast of the target and the luminance of the rest of the visual field are important because the luminance of the scattered light is superimposed on the luminance of the target and its background. The impact of scattered light is diminished when the luminance contrast of the target is high and the background luminance is high.

The simplest approach to minimizing disability glare for electric lighting is to use only luminaires in which there is no view of the light source, either directly or as a specularly reflected image, from common lines of sight, and to position the luminaires so that they are as far as possible from the common lines of sight. By restricting the view of the light source, the maximum luminance of the luminaire is reduced; by placing it far away from common lines of sight, the amount of light that is scattered onto the part of the retinal image representing what needs to be seen is also reduced. As for windows, the luminance of the window can be reduced by the use of tinted glass, electrochromic glazing or various types of blinds, some of which will preserve a diminished version of the view out. However, if the sun is directly visible through the window, there is no alternative but to use an opaque cover. Increasing the deviation from the line of sight is usually a matter of moving what has to be seen away from the window. These actions will also be effective in reducing discomfort glare.

All the above approaches have been concerned with alleviating vision loss, but it should be recalled that the circadian timing system also deteriorates with age. The rational approach to this deterioration is to seek exposure to greater amounts of light, particularly short-wavelength light, so as to increase the level of stimulation. Sadly, this is not what happens for many of the elderly, particularly if they are institutionalized (Cambell et al., 1988; Shochat et al., 2000). Rather, many of the elderly received much lower levels of light exposure than they should. The most obvious solution to this problem is greater exposure to sunlight, but if this is not possible, then Mishima et al. (2001) have shown that electric light therapy producing exposure to 2500 lx at the eye from full-spectrum fluorescent lamps for 2 h, twice daily, can restore melatonin amplitudes and reduce insomnia in elderly patients. Much lower illuminances could almost certainly be used to produce such effects if a spectrum rich in the short-wavelength end of the visible spectrum was adopted.

Ideally, a single lighting installation should be able to provide the necessary stimulation for both the visual system and the melatonin-based circadian timing. Figueiro (2008b) has proposed a 24 h lighting schedule for the elderly designed to provide a high level of circadian stimulation during the day, low circadian stimulation during the night, good visual conditions during the waking hours and a night-light that ensures safe movement at night without disrupting sleep. The schedule recommends at least 400 lx of circadian-effective light at the cornea during the day, no more than 100 lx of circadian-ineffective light at the cornea during the evening and no more than 5 lx of circadian-ineffective light at the cornea during the night. Circadian-effective light is rich in short-wavelength power (see Section 3.4.3); circadian-ineffective light is not.

Of course, these recommended illuminances have to be delivered in such a way that there is enough light on relevant tasks and at the eye, without glare but with good colour rendering. Unfortunately, there has been little consideration of how to do this. Rather, design advice has concentrated on lighting for enhancing the vision of the elderly. Specific advice is given by both international and national lighting authorities (CIE, 1997; IESNA, 2008) and by organizations devoted to the welfare of elderly, including those with vision loss (Figueiro, 2001; Thomas Pocklington Trust, 2010). Following this advice should lead to improvement in visual capabilities for the elderly and for many people with vision loss. Further, young people will not experience any loss in visual function following the provision of such lighting, although whether they will appreciate being given 'old peoples' lighting' is doubtful. It is also important to note that even if lighting is appropriate for the elderly, the deterioration in the retinal and cortical processes that also occur with increasing age implies that any enhancement in visual function that occurs will most likely be limited. Nonetheless, for the elderly and those who have to live with vision loss, any enhancement of their visual functions is welcome and may have a wider impact on their quality of life (Sorensen and Brunnstrom, 1995). Attention should now be given to the problem of designing lighting for the elderly so as to enhance their circadian functions without negatively influencing their vision.

13.8.4 Eliminating the Task

The final approach that can be used to offset the effects of age on vision is to eliminate the need to do the task. This approach is evident in the common observation that elderly drivers give up driving at night while still feeling able to drive safely during the day. Being able to drive makes an important contribution to the independence and quality of life of the elderly (Jette and Branch, 1992). Many are reluctant to give up driving until forced to by circumstances beyond their control, medical problems related to vision loss being one of the most common circumstances (Campbell et al., 1993). Before this stage is reached, many of the elderly will recognize the stress of driving at night, in conditions of low luminance and in the presence of opposing headlights producing glare. The usual response is to time their journeys so that they can be completed before nightfall.

Deciding not to drive at night is a change in behaviour in response to difficult visual conditions that cannot easily be changed. The other side of this coin is the possibility of maintaining behaviour and changing the visual conditions to make them less difficult. An example of this is the use of transition zones between areas lit to very different illuminances. People with glaucoma, and other causes of vision loss that affect rod photoreceptors, often experience delayed and diminished dark adaptation (CIE, 1997). This makes it difficult for them to move safely from a brightly lit space to one that is dimly lit, for example, from the interior of a building to the car park at night. Lighting can overcome this problem by eliminating the need for much dark adaptation. The features of the lighting that need attention if this approach is to be used are the range of adaptation luminances between the interior and the exterior, the grading of luminance between the interior and exterior so that a sudden change in luminance is avoided and, of course, the control of glare.

13.9 SUMMARY

As people age, a number of changes in the eye occur. With increasing years, the ability to focus close up is diminished; the amount of light reaching the retina is reduced, particularly short wavelength light; more of the light reaching the retina is scattered; and more stray light is generated inside the eye. These changes start in early adulthood and increase in form and magnitude with increasing age. The consequences of these changes with age for the capabilities of the visual system are many and varied. At the threshold level, old age is characterized by reduced absolute sensitivity to light, reduced visual acuity, reduced contrast sensitivity, reduced colour discrimination, smaller visual fields and greater sensitivity to glare. Outside the laboratory, the elderly have difficulty with seeing in dim light, moving from bright to dark conditions suddenly, reading small print and distinguishing dark colours.

The changes in the eye that occur with age also affect the circadian timing system. The intrinsically photosensitive retinal ganglion cells of the retina that feed signals to the suprachiasmatic nuclei are most sensitive to short-wavelength light so the reduction in light, particularly short-wavelength light, that reaches the retina is detrimental to the functioning of the circadian timing system. This means the elderly are more likely to suffer from circadian disruption with consequences for many physiological and psychological functions.

These changes with age are the best that can be expected. With increasing age comes a greater likelihood of pathological changes in the eye leading to vision loss culminating in blindness. Vision loss is a state that falls between normal vision and blindness. Globally, the five most common causes of vision loss are refractive error, cataract, macular degeneration, glaucoma and diabetic retinopathy. These causes involve different parts of the eye and have different implications for how lighting might be used to help people with vision loss. Refractive error means that the image of the outside world is not focused on the retina. Cataract is an opacity developing in the lens. The effect of cataract is to absorb and scatter more light as the light passes through the lens. This results in reduced visual acuity, reduced contrast sensitivity and degraded colour vision, as well as greater sensitivity to glare and reduced stimulation of the circadian timing system. Macular degeneration occurs when the macula, which covers the fovea, becomes opaque. An opacity immediately in front of the fovea implies a serious reduction in visual acuity and in contrast sensitivity at high spatial frequencies. Typically, these changes make seeing detail difficult if not impossible. However, peripheral vision is unaffected so the ability to orient oneself in space and to find ones way around is little changed. Glaucoma is shown by a progressive narrowing of the visual field. Glaucoma is due to an increase in intraocular pressure which damages the blood vessels supplying the retina. Glaucoma will continue until complete blindness occurs unless the intraocular pressure is reduced. Diabetic retinopathy is a consequence of chronic diabetes mellitus and effectively destroys parts of the retina through the changes it produces in the vascular system that supplies the retina. The effect these changes have on visual capabilities depends on where on the retina the damage occurs and the rate at which it progresses, but all are characterized by large differences between individuals.

These changes with age can be compensated, to some extent. The limited range of focus of the elderly can be overcome by the use of spectacles or contact lenses. The tasks they have difficulty with can be redesigned to make them visually easier. This usually involves increasing the luminance contrast of the task details, making the task details bigger and using more saturated colours. Lighting can also be used to compensate for aging vision. The elderly benefit more from higher illuminances than do the young, but simply providing more light may not be enough. The light has to be provided in such a way that both disability and discomfort glare are carefully controlled and veiling reflections are avoided. People with vision loss may or may not benefit from such changes in lighting depending on the specific cause of the loss. However, there is one approach which is generally useful. This approach is to simplify the visual environment and to make its salient details more visible by attaching high-luminance contrast to those details and only to those details.

As for the circadian timing system, the effects of age can be offset to some extent by increasing light exposure during the day and limiting it at night. Exposure to sunlight either by being outdoors or in a sunroom is the ideal but where this is not available, electric lighting with a lot of short-wavelength visible radiation can be an adequate substitute.

Specific advice on lighting appropriate for different activities by the elderly is given by both international and national lighting authorities and by organizations devoted to the welfare of the elderly. Following this advice should lead to improvements in visual function for the elderly and for many people with vision loss without causing problems for young people. For the elderly and those who have to live with vision loss, any enhancement of their visual function is welcome and may have a wider impact on their quality of life. Attention should now be given to generating advice on how to provide lighting that is effective in maintaining circadian function without negatively affecting vision.

14 Light and Health

14.1 INTRODUCTION

Exposure to light can have both positive and negative impacts on human health, impacts that can become evident soon after exposure or only after many years. Unfortunately, health is an elastic term that can be stretched from the trivial to the fatal, from the individual to the population. Here, the impacts of lighting on health to be considered are limited in four ways. First, the impact is focused on the individual not on the population. Second, only impacts that have the potential to affect the health of many individuals are considered. Third, the aspects of health being considered are those for which an individual would be wise to seek out the services of a medical professional, although that professional's expertise might vary from ophthalmology through dermatology and oncology to psychiatry. Fourth, the impacts are those where there is a well-established epidemiological link between light exposure and health with or without a plausible mechanism through which light can have its effect or where light exposure has been used as a treatment for a condition and clinical trials have demonstrated the effectiveness of that treatment. In other words, this chapter is devoted to the proven effects of light exposure on the health of many individuals. Aspects of light and health that are matters of faith such as colour therapy are not considered, neither are the more nebulous outcomes often associated with claims of well-being.

14.2 LIGHT AS RADIATION

People typically spend many hours of their lives bathed in electromagnetic radiation in the ultraviolet (UV), visible and infrared (IR) wavelength ranges. This radiation can have an effect on human health simply as radiation, regardless of whether or not it stimulates the visual system or the non-image-forming system.

14.2.1 Tissue Damage

Body tissue can be damaged by many different means. The causes of damage can be broadly classified as mechanical, thermal, chemical and biological. The type of tissue damage of interest here is that caused by exposure to electromagnetic radiation in the UV, visible and IR wavelength regions of the electromagnetic spectrum (see Figure 1.1). At first, the decision to include UV and IR irradiation in a book devoted to the effects of light may seem odd. It can be justified by the fact that many light sources produce UV and IR radiation as well as visible radiation and some light sources are deliberately designed to produce primarily UV or IR radiation for example, fluorescent lamps used in sunbeds and halogen lamps used for industrial drying. Therefore, anyone who is using light sources should be aware of their potential for tissue damage, and that means considering UV and IR radiation as well as visible radiation.

14.2.1.1 Tissue Damage by UV Radiation

The Commission Internationale de l'Eclairage (CIE) has divided the UV components of the electromagnetic spectrum into three regions, UV-A (400–315 nm), UV-B (315–280 nm) and UV-C (280–100 nm). A part of the UV-A region (400–380 nm) stimulates the visual system, although according to this definition it is formally part of the UV radiation. Exposure to UV radiation affects both eye and skin. For the eye, exposure to UV radiation can produce photokeratitis. This is a very unpleasant but temporary condition that can result in severe pain beginning several hours after exposure and persisting for 24 h or longer (Pitts and Tredici, 1971). The symptoms of photokeratitis are clouding of the cornea, reddening of the eye, tearing, photophobia, twitching of the eyelids and a feeling of grit in the eye. Typically, all these symptoms clear up within about 48 h. Photokeratitis is an occupational hazard for electric arc welders (welders' flash) and polar explorers (snow blindness), the former because the electric arc produces copious amounts of UV radiation and the latter because snow reflects UV radiation very effectively. The factors that determine whether or not a person exposed to UV radiation will experience photokeratitis are the dose, that is, the product of the irradiance of the cornea and the duration of the exposure, and the actual spectrum of the exposure. Irradiance in the wavelength range 200–400 nm is what causes photokeratitis, the effect being greatest for wavelengths around 270 nm (Zuclich, 1998).

Photokeratitis occurs because of a photochemical reaction to UV radiation at the cornea, but not all the UV radiation incident on the eye is absorbed at the cornea. A significant amount of UV radiation reaches and is absorbed by the lens. The effect of exposing the lens to UV radiation in the range 250–280 nm is to produce a cataract (see Section 13.4), an opacity in the lens that absorbs and scatters light, thereby severely degrading the retinal image, so much so that vision loss occurs (Collman et al., 1988; Okuno et al., 2012).

Exposure to UV radiation also has an effect on the skin. Within a few hours of exposure, the skin reddens. This reddening is called erythema. Erythema reaches a maximum about 8–12 h after exposure and fades away after a few days. High-dose exposures may result in oedema, pain, blistering and, after a few days, peeling of the skin, that is, sunburn. Studies of the action spectrum for erythema have a long history resulting in an internationally agreed action spectrum (CIE, 1998b) (Figure 14.1). This action spectrum indicates that the most effective wavelengths for causing erythema lie in the UV-B range. Besides the international CIE standard, there are several other versions of the erythemal action spectrum in use, so when assessing data, it is always necessary to know which version has been used (Webb et al., 2011)

Repeated exposure to such UV radiation produces a protective response in the skin. Specifically, with repeated exposure, pigment migration to the surface of the skin occurs and a new darker pigment is formed. Coincident with this, the outer layer of the skin thickens producing what used to be a socially acceptable tan, the strength of the tan depending on skin type. The effect of these changes is to decrease the sensitivity of the skin to UV radiation. It is just as well this screening process occurs because frequent and prolonged exposure of the skin to

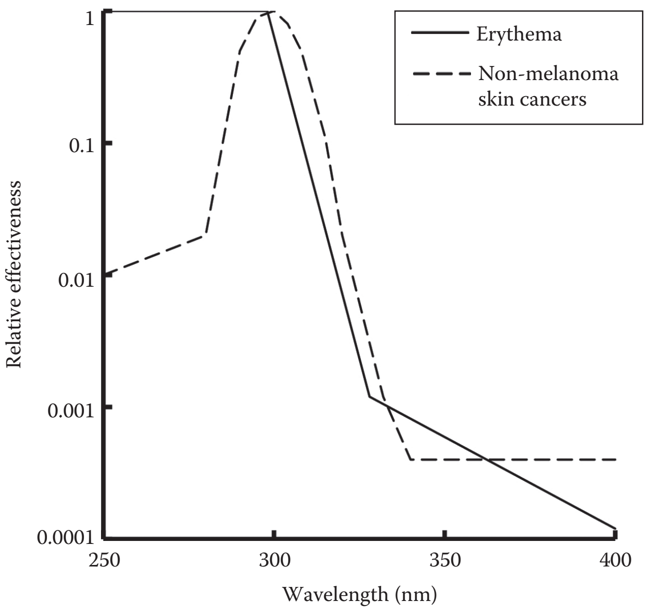


FIGURE 14.1 Action spectra for erythema and for non-melanoma skin cancers. (After Commission Internationale de l'Eclairage (CIE), *Erythema Reference Action Spectrum and Standard Erythemal Dose*, CIE Publication S 007: Joint ISO/CIE Standard, CIE, Vienna, Austria, 1998b; Commission Internationale de Eclairage (CIE), *Photocarcinogenesis Action Spectrum (Non-Melanoma Skin Cancers)*, CIE Publication S 019, Joint ISO/CIE Standard, CIE, Vienna, Austria, 2006b.)

UV radiation is associated with skin aging and increases the risk of developing certain types of skin cancer (Freeman et al., 1970). Skin cancer comes in three forms: basal cell, squamous cell and malignant melanoma. The CIE has produced an action spectrum for the basal and squamous forms (CIE, 2006b) (Figure 14.1). However, all show positive correlations with exposure to UV radiation from the sun (Moan and Dahlback, 1993), which is why the WHO recommends limiting time in the midday sun, wearing protective clothing in strong sunshine and applying sunscreen creams. Conventional electric lighting produces very small amounts of UV radiation, but sunbeds do produce significant quantities, as they have to if they are to generate a tan for the user. The WHO recommends that the use of sunbeds should be regulated and their use by people under the age of 18 restricted.

14.2.1.2 Tissue Damage by Visible and Near-IR Radiation

Electromagnetic radiation in the wavelength range 400–1400 nm can damage the retina, because radiation in this wavelength range, unlike UV radiation, is transmitted through the ocular media and so reaches the retina. On arriving at the retina, most photons are absorbed in the photoreceptors, but some are absorbed in the pigment epithelium thereby increasing its temperature. Given enough energy, the temperature of the pigment epithelium can be elevated sufficiently to damage the tissue. This effect goes under the name of chorio-retinal injury. Such injuries have a long history, mostly derived from looking directly at the sun for a prolonged period. The main symptom of chorio-retinal injury is the presence of a blind spot or scotoma in the area where the absorption occurred. The location of the injury is important. If it occurs in the fovea, then it severely interferes with vision. If it is small and occurs in the far periphery, it may pass unnoticed. The scotoma can usually be seen under ophthalmic examination within 5 min of exposure and certainly within 24 h. Recovery from chorio-retinal injury ranges from limited to non-existent.

The probability of chorio-retinal injury by exposure to visible and near-IR radiation basically depends on the retinal radiant exposure, weighted by the appropriate action spectrum. The action spectrum for chorio-retinal injury, derived from the rhesus monkey (Lund, 1998), has shown that the most sensitive wavelength region is from 400 to 1000 nm (Figure 14.2). Of course, monkeys are not human, but comparison studies have shown reasonable agreement between the retinal radiant exposures necessary to damage the retina in monkeys, rabbits and humans (Geeraets and Nooney, 1973).

Another factor that is important for chorio-retinal injury is the size of the retinal image. The relevance of retinal image size is simply that tissues in the retina can much more easily conduct heat away from the point of absorption for small retinal images, say less than 50 μm in diameter, than for large retinal images sizes, for example, 1000 μm. Therefore, large retinal images are much more likely to damage the retina than will a small area of the same retinal irradiance. Yet another factor

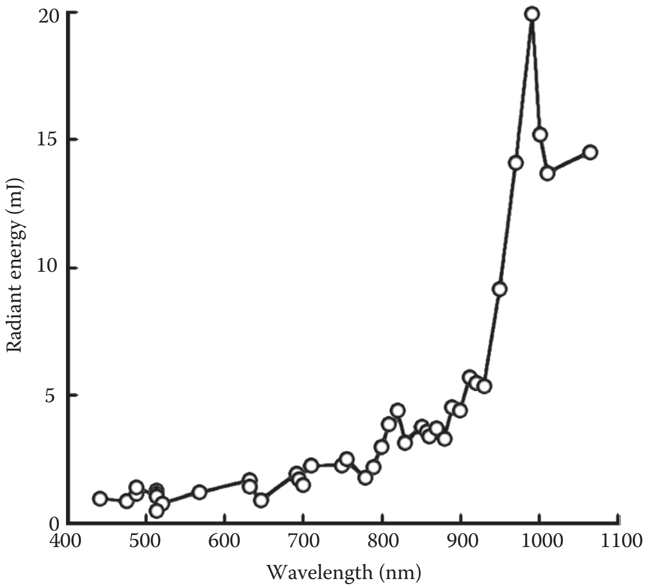


FIGURE 14.2 An action spectrum for chorio-retinal injury in the rhesus monkey presented as the radiant energy necessary for a 50% probability of producing an alteration in the appearance of the retina 1 h after a 100 ms exposure, plotted against wavelength. (After Lund, D.J., Action spectrum for retinal thermal injury, in R. Matthes and D. Sliney (eds.), *Measurements of Optical Radiation Hazards*, International Commission on Non-Ionizing Radiation Protection, Oberschleißheim, Germany, 1998.)

is the duration of exposure. This can be divided into two parts, longer and shorter than 150 ms. This time is of practical importance because it approximates to the time required for the operation of a simple mechanism used to protect the eye, the aversion response. The usual response to seeing a very bright light, which is what a high retinal irradiance in the wavelength range 380–780 nm will look like, is to blink and look away. These movements have a reaction time of 150–300 ms. For exposure times below 150 ms, no avoiding action is possible. Fortunately, very high retinal irradiances are required to produce a damaging radiant exposure in such short times, very much higher than are produced by any form of conventional lighting. For example, for an exposure of 100 ms, retinal irradiances from about 50 to 1000 W/cm^2, depending on the retinal image size, are necessary for injury to occur. For exposure times above 150 ms, lower retinal irradiances will cause injury, but the probability that this will occur is reduced by the ability to take avoiding action. The most dangerous situation is if a source were to produce a lot of radiation in the near IR, that is, the wavelength range 780–1400 nm and very little in the visible. In this situation, there would be no high brightness cue to trigger the protective aversion response.

All the earlier discussion of chorio-retinal damage has been concerned with thermal damage to the retina. Unfortunately, there is also the possibility of rapid photochemical damage of the retina occurring following exposure to visible wavelengths. This is called photoretinitis. The exact nature of the chemical process by which photoretinitis occurs is not understood, but what is known is that it can occur at radiant energy levels less than those required to cause threshold thermal damage. The most effective wavelengths are in the range 400–500 nm (Figure 14.3) which explains its original name of blue-light hazard (Bullough, 2000). Photoretinitis is rare in practice because the normal aversion to very bright lights causes people to shield their eyes

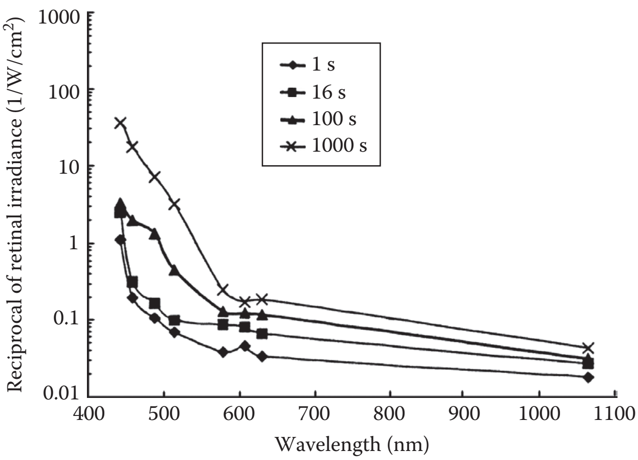


FIGURE 14.3 Action spectra for threshold photoretinitis, defined as a minimally visible retinal lesion 48 h after exposure, for exposure durations of 1–1000 s. The data are from Ham et al. (1976) for nonhuman primates. (After Stuck, B.E., The retina and action spectrum for photoretinitis ('blue light hazard'), in R. Matthes and D. Sliney (eds.), *Measurements of Optical Radiation Hazards*, International Commission on Non-Ionizing Radiation Protection, Oberschleißheim, Germany.)

or to look away before damage can occur. However, if exposure is sufficient to cause photoretinitis, the damage will not usually become apparent until about 12 h later. Some recovery from the damage is possible.

14.2.1.3 Tissue Damage by IR Radiation

The CIE has treated the IR region of the electromagnetic spectrum in the same way as the UV region, that is, it has divided it into three parts: IR-A (780–1,400 nm), IR-B (1,400–3,000 nm) and IR-C (3,000–1,000,000 nm). Measurements of the spectral transmittance of the ocular media have shown that wavelengths up to 1400 nm reach the retina, although an increasing amount of radiation is absorbed in the lens with increasing wavelength. Between 1400 and 1900 nm, virtually all incident radiation is absorbed in the cornea and aqueous humour. Above 1900 nm, the cornea is the sole absorber. The effect of energy in the IR-A region that reaches the retina has already been considered in the discussion of chorio-retinal damage. However, IR energy that is absorbed either in the ocular media or in the cornea and lens also needs to be considered because it raises the temperature of the tissue where it is absorbed and may, by conduction, raise the temperature of adjacent areas. Fortunately, extremely high corneal irradiances, of the order of 100 W/cm^2, are necessary for changes in the lens to occur within the time taken for the common aversive reaction to occur. Further, only 10 W/cm^2 absorbed in the cornea will produce a powerful sensation of pain which should trigger the aversive response. It is generally considered that the aversive reaction provides protection for the eye against thermal effects of IR radiation up to levels in excess of those that cause a flash burn of the skin.

So far, only the acute effect of IR radiation has been considered, but there are definitely adverse effects following prolonged exposure to IR radiation. Lydahl and Philipson (1984a,b) have shown an increased incidence of cataract among workers who have been exposed to molten glass or metal for many years. This is believed to be a thermal effect, caused by absorption of IR-A and IR-B radiation (ICNIRP, 2006). Recommendations for limiting exposure to IR radiation have been developed (see Section 14.2.2). In practice, the important point to note is that whenever exposure to a light source produces a marked sensation of warmth on the skin, the possibility of long-term IR radiation damage to the eye should be considered.

As for the skin itself, the effect of visible and IR radiation is simply to raise the temperature. If the temperature elevation is sufficient, usually to more than 45°C, then burns will be produced. It is important to realize that the focusing process of the eye makes the eye much more sensitive than the skin to such injury for visible radiation and IR-A radiation. However, the skin and eye are equally at risk from IR-B and IR-C radiations because the ocular media are virtually opaque for these wavelengths and the mechanism for acute damage is thermal. The efficiency with which a given irradiance raises the temperature of the skin depends on the exposed area, the reflectance of the skin and the duration of exposure. The threshold irradiance for thermal injury of the skin is greater than 1 W/cm^2. Such irradiances are very unlikely to be produced by sunlight or conventional lighting of interiors, so such sources are unlikely to produce any degree of thermal injury to the skin by radiation. In any case, for anything other than very short exposure times, considerations of heat stress become relevant before thermal damage can occur.

14.2.2 Threshold Limit Values

Given the potential for tissue damage by UV, visible and IR radiation, it should not be too surprising that there are recommended limits to exposure to such radiation, and given the universality of the phenomena, it should also come as no surprise that there are a number of bodies making such recommendations. The first organization to make recommendations limiting exposure was the American Conference of Governmental Industrial Hygienists (ACGIH). This is an independent, professional society dedicated to the advancement of occupational and environmental health. Its best-known contribution to protecting health has been the publication of threshold limit values for exposure to chemical and physical agents. The threshold limit values are levels of exposure and conditions under which it is believed, based on the best available scientific evidence, that nearly all healthy workers may be repeatedly exposed, day after day, without adverse health effects. The ACGIH publishes threshold limit values for exposure to UV radiation, to avoid photokeratitis; for exposure to visible radiation, to avoid photoretinitis; and for visible and IR radiation to avoid cataract after prolonged exposure and chorio-retinal injury from low-luminance IR irradiation sources. The threshold limiting values take various forms depending on the size of the source of radiation and the exposure time. For some situations, the threshold limit values are based on total irradiance at the eye, while for others, they are based on the spectral irradiance at the eye or the spectral radiance of the source, multiplied by a weighting function based on the action spectrum of the damage being controlled. The recommendations of the ACGIH have been adopted by the IESNA and, with slight modifications, by the International Committee on Non-Ionizing Radiation Protection, the CIE and the countries of the European Union. Following any of these recommendations will limit the likelihood of tissue damage by UV, visible and IR radiation. Full details of the threshold limit values and the associated maximum permissible exposures can be obtained from the publications of the organizations mentioned (ICNIRP, 1997, 2004, 2006; CIE, 2002c; IESNA, 2005b; BSI, 2008).

14.2.3 Hazardous Light Sources

The IESNA Recommended Practice 27 has been adopted as an American National Standard (IESNA, 2005b, 2007a, 2009). It sets out a system for measuring, classifying and labelling light sources according to the hazard their optical radiation represents. This system has four classes: exempt group and risk groups 1, 2 and 3. Exempt light sources are those that do not pose any photobiological hazard from UV, visible or IR radiation. Any light source that is assigned to risk groups 1, 2 or 3 must exceed one or more of the criteria used for the exempt group. The philosophical basis for risk group 1 (low risk) is that light sources in this group exceed the limits set for the exempt group but do not pose a hazard due to normal behavioural limitations on exposure. The philosophical basis for risk group 2 (moderate risk) is that light sources in this group exceed the limits set for the exempt group and risk group 1, but do not pose a hazard due to the aversive response to very bright light or to thermal discomfort. Any light source in risk group 3 (high risk) is believed to pose a hazard, even for momentary exposures. The criteria defining risk groups 1, 2, and 3 are the same as those for the exempt group, but the maximum permitted exposure times are reduced. Lamps falling into the higher risk groups should carry a warning label, indicating the nature of the hazard and suggested precautions that should be taken. The European Union has adopted a similar approach in its standard (BSI, 2008).

Most light sources used for general lighting, such as fluorescent discharge, HPS discharge and light-emitting diodes (LEDs), fall into either the exempt group or risk group 1. Some high-wattage tungsten halogen and MH light sources can fall into risk groups 2 or 3. Of all light sources, the one to which most people are exposed and which represents the greatest potential for tissue damage is the sun. When overhead, the sun emits copious amounts of UV, visible and IR radiation and easily falls into risk group 3. It is the realization of the hazard represented by exposure to optical radiation from the sun that has driven the development of more effective sunscreens to be applied to the skin (Forestier, 1998) and sunglasses to shield the eyes (Sliney, 1995; Mellerio, 1998).

It is important to appreciate that these observations about the potential for tissue damage posed by various light sources are gross generalizations. The measurements used to classify a given light source are made under what are called normal intended conditions. For the exempt group, normal intended conditions are defined as being viewed or exposed at a distance such that 500 lx falls on the cornea or, if 500 lx is provided at less than 20 cm from the exterior surface of the lamp, at a fixed distance of 20 cm. Exposure time is fixed by category and based upon the intensity and the potential for damage by the spectrum involved. For instance, if a general lighting fluorescent lamp were to be evaluated, it would meet the requirements of the exempt group only if it did not exceed the UV exposure limits within an 8 h period and a near-UV or near-IR cornea/lens hazard within 1000 s and a retinal thermal hazard within 10 s and a blue-light hazard within 2.8 h.

Further, the classification should not be taken to apply to all lamps of a given type. For example, while fluorescent lamps used for general lighting fall into the exempt group, there are fluorescent lamps used for sunbeds that are designed to emit considerable UV radiation and these are not exempt. Similarly, some mercury discharge lamps are designed not as light sources, but rather as sources of UV radiation for germicidal purposes. For the sun, the hazard posed depends on the path length through the atmosphere and the skin pigmentation of the individual. There is little hazard when the sun is low in the sky, and the darker the skin pigmentation, the less the risk at all sun elevations.

The safest principle to follow when evaluating the potential for tissue damage from any specific light source is to check that it has been tested against one of the available standards, to assess the relevance of that standard for the proposed application and, if appropriate, to follow the actions suggested for the allocated risk group. If the standard is not appropriate for the application, then it is necessary to go back to fundamentals and make an individual assessment of the risk of tissue damage.

14.2.4 Practical Considerations

The key word when considering the optical radiation hazards posed by different light sources is potential. Whether the potential for tissue damage indicated by the risk classification of the light source turns into actual damage depends on how the light source is used. Light sources are normally used in luminaires, and placing the light source in a luminaire may dramatically change the spectrum of the radiation received by the viewer. For example, the UV radiation emitted by tungsten halogen lamps can be much reduced by using a glass cover, and dichroic reflectors can be used to transmit IR radiation while reflecting visible radiation. Mostly, the placing of a light source in a luminaire reduces the level of hazard posed by optical radiation, but where the filtering is inadequate, a dangerous level of exposure can occur (O'Hagan et al., 2011). This means that for any light source other than one in the exempt category, it is necessary to know the spectral characteristics of the luminaire materials particularly as different plastics and glasses have very different UV transmittances (McKinlay et al., 1988; Lambrechts and Rothwell, 1996).

Another factor that will change the spectrum of the radiation received by the viewer is what proportion of the radiation incident comes directly from the light source. The larger is the proportion of radiation received after reflection, the more likely it is that the spectral content will be changed, because there is no guarantee that the reflecting surface reflects UV, visible and IR radiation equally. For example, snow reflects about 88% of UV-B radiation multiplied by the ACGIH actinic UV weighting function, while grass reflects less than 2%. What this variability implies is that where there is doubt about the risk of tissue damage by radiation from light sources, field measurements of the actual spectral radiance or irradiance are essential. If such measurements show that the hazard is actual rather than potential, then action should be taken to reduce the hazard. Ideally, this would take the form of either reducing the output from the light source to below that needed to create a hazard or reducing the exposure time. This is not always possible, either because the radiation is an inevitable product of the work being done, for example, around a furnace, or is required to produce a particular effect on some component of the work, for example, UV curing of dental fillings. In these circumstances, a degree of protection is required. This can take the form of screening the source with suitable materials, that is, those opaque to the damaging radiation and/or personal protection in the form of eye filters, helmets and clothing.

14.2.5 Special Groups

All the methods for evaluating light sources for tissue damage are based on action spectra linked to the average adult human response to UV, visible and IR radiation. Unfortunately, there are some groups who deviate markedly from that average sensitivity in the direction of making them much more sensitive to radiation in these wavelength ranges.

One such group consists of premature babies, particularly those weighing less than 1000 g at birth. These infants have eyes that are still developing, and exposure to light is believed to be involved in the retinopathy of prematurity, a visual disorder that can permanently damage the retina of such babies. Proposals to limit the light exposure of babies in neonatal intensive care units have been made (Bullough and Rea, 1996). Even babies born after a normal gestation period have to be treated with care as regards light exposure because such infants have lenses with significant transmittance in the wavelength range from 300 to 350 nm, that is, in the UV-B and UV-A regions (Barker and Brainard, 1991). This means care should be taken to limit the exposure of the eyes of newborns to light sources that emit a lot of UV radiation, such as the sun when it is high in the sky. Given the evidence that enhanced UV transmittance is still evident in young children (Sanford et al., 1996), this care should be continued for several years.

There is also concern about the use of LEDs containing peak emissions in the 440–460 nm range in childcare centres (Zak and Ostrovsky, 2012). Most white LEDs based on the use of a blue LED and a phosphor have such emissions (see Figure 1.13). The concern is based on the fact that the transmittance of the ocular media for such wavelengths is much greater in children than adults, so there is an enhanced risk of photochemical damage to the retina.

Another group with a problem with exposure to light, but at the opposite end of life, is post-operative cataract patients who have had their lens removed, that is, patients who are aphakic. Such patients are much more likely to suffer photochemical retinal damage due to short-wavelength visible and UV radiation exposure than are people with their biological lens intact, unless they are fitted with a UV-absorbing, intraocular lens (Werner and Hardenbergh, 1983; Werner et al., 1990; CIE, 1997). The ACGIH has recognized the hazard for aphakics by introducing a hazard weighting function specifically for this condition.

Three other groups who need to take special care about exposure to UV radiation are those who have medical conditions that enhance photosensitivity, for example, lupus erythematosus (Rihner and McGrath, 1992); those who are taking pharmaceuticals that increase photosensitivity; and those who are exposed to certain chemical agents in the environment, such as the whiteners used in some household products (Harber et al., 1985). Unlike newborns and aphakics, where the hazard is confined to the retina, the effect of increased photosensitization primarily increases the hazard to the skin. How much the risk posed by exposure to UV radiation is increased will depend on the medical condition or the specific pharmaceutical or chemical and the dose taken or level of exposure.

14.2.6 Positive Effects

So far, the impacts of optical radiation on health have all been negative, but there are some positive effects.

14.2.6.1 Air Purification

UV-C radiation destroys DNA, making lamps with emissions in this range effective in killing microorganisms. This can have indirect health benefits for humans when used to purify air, liquids such as water and milk, and granular material such as sugar. UV-C radiation purifies by deactivating pathogens such as fungal spores and bacilli (Brickner et al., 2003; First et al., 2007a). UV radiation as an air disinfection technique has a long history and, after a period of neglect, has reappeared as an attractive technology for controlling the spread of drug-resistant tuberculosis (Reed, 2010). Germicidal lamps operate by passing an electric current through a low-pressure mercury vapour, the vapour being enclosed in a special glass or quartz tube that transmits UV radiation. Most of the energy emitted by such lamps is at 254 nm. Such lamps may be used in any setting where there is a need to limit the spread of disease through the air, including hospitals, schools and shelters for the homeless. However, as UV-C radiation is dangerous to both eyes and skin, protective measures are needed where such lamps are in use. Installations are safe, provided that the occupants of the space cannot directly view the lamps and the room surfaces are minimally reflective of the UV-C wavelengths (Nardell et al., 2008). Technical guidance on how to successfully install such air purification systems is emerging, and new techniques are under development (First et al., 2007b; Rudnick et al., 2009).

14.2.6.2 Phototherapy: Hyperbilirubinemia

There are also a number of other medical conditions where exposure to light as radiation has been shown to be helpful (Parrish et al., 1985). Hyperbilirubinemia, commonly known as jaundice of the newborn, occurs frequently enough so that about 7%–10% of babies born in the United States require medical attention. Severe cases can lead to brain damage and death. The phototherapy for this condition involves exposing the naked baby to short-wavelength visible radiation, with the eyes shielded (Bullough and Rea, 1996).

14.2.6.3 Phototherapy: Skin Diseases

UV radiation is also used in the treatment of skin diseases such as psoriasis and eczema. Patients are given multiple whole-body exposures to sub-erythemogenic doses of UV-B radiation. One treatment for severe psoriasis, eczema, vitiligo and some other skin disorders uses a combination of exposure to UV-A radiation and a psoralen. This combined treatment is known as photochemotherapy. Chemotherapy operates by killing cells. The general problem of chemotherapy is how to limit this destruction to the desired cells. Psoralen has the potential to kill cells, but it requires exposure to UV-A to trigger the effect. Fortunately, UV-A radiation penetrates the skin but does not reach internal organs, so the combination of psoralen and UV-A radiation limits the cytotoxic effects to the skin. This should not be taken to mean that photochemotherapy is without risk. Basal and squamous cell skin cancers have been found in patients who have been treated by photochemotherapy. As in so many medical problems, the decision whether to use photochemotherapy or not is a matter of balancing one risk against another.

14.2.6.4 Phototherapy: Internal Tumours

Photochemotherapy can also be used to treat internal tumours. A chemical, which when injected into the bloodstream binds to tumour cells, is triggered by exposure to visible radiation of 630 nm to kill tumour cells delivered via an endoscope. This process, which is also known as photodynamic therapy, has been shown to be effective against a wide range of tumours (Epstein, 1989).

14.2.6.5 Phototherapy: Immune System

One other use of UV radiation is in the suppression of the immune system (Noonan and de Fabo, 1994). Such suppression may be helpful in the treatment of autoimmune diseases such as multiple sclerosis where hyperactivity of the immune system is a problem. Of course, it may also be dangerous for people who have already been immunosuppressed. Therapeutic exposure to UV should only be undertaken after consulting a qualified physician.

14.2.7 Aging Effects

In addition to the hazards and benefits of exposure to UV, visible and IR radiation discussed earlier, there are also possible effects of such exposure on the rate at which aging progresses. One example is the possibility of a link between the total light exposure over life and the likelihood of retinal damage. The proposed mechanism is that exposure to light causes damage to the retina. This damage can be repaired but the repair mechanisms become less effective with age, resulting in damage that accumulates more rapidly with greater retinal exposure to light (Marshall, 1987). There is no doubt that the probability of retinal deterioration increases with age, and there are close similarities between the changes induced in the retina as a result of the aging process and those elicited by exposure to high levels of illumination (WHO, 1982), but whether it is really exposure to light that is responsible for the aging process in the retina or some other mechanism is open to question (Weale, 1992). What is needed are comprehensive epidemiological studies examining the link between light exposure history and retinal deterioration with age. Until they are done, the effect of prolonged exposure to high levels of light on the rate of aging of the retina must remain unproven.

The other aging effect of prolonged exposure to radiation is well established and affects the skin. The most striking feature of severely photo-aged skin is the presence of massive quantities of thickened, degraded elastic fibres that degenerate into amorphous masses. The result is a thicker skin resembling a crust. Photo-aging is most commonly seen on the parts of the body that are not usually protected by clothing. The action spectrum for photo-aging is not well defined, but it is clear that the dominant radiation is in the UV region (Cesarini, 1998). Wearing a sunscreen while outdoors, particularly in regions where sunlight is copious, will provide some protection against the photo-aging process.

14.3 LIGHT OPERATING THROUGH THE VISUAL SYSTEM

The function of the visual system is to help us make sense of the visual environment around us. How well we can see may affect how we understand that environment and that in turn can affect our health.

14.3.1 Eyestrain

Light is a necessity for the visual system to operate, but if used in the wrong way, it can be injurious to health. The most common effect of lighting operating through the visual system on health is colloquially known as eyestrain or more formally as asthenopia. Eyestrain is the result of prolonged experience of lighting conditions that cause discomfort. What those conditions are is fully discussed in Chapter 5.

The symptoms of eyestrain are irritation of the eyes, evident as inflammation of the eyes and lids; breakdown of vision, evident as blurring or double vision; and referred effects, usually in the form of headaches, indigestion, giddiness, etc. Anyone who experiences eyestrain frequently can hardly be said to be enjoying the best of health.

The symptoms of eyestrain are likely to appear whenever the visual system is faced with a difficult visual task, under- or overstimulation, distraction or perceptual confusion (see Section 5.3). These conditions can be brought about either by poor lighting, the inherent features of the task and its surroundings, the limitations of the individual's visual system or some combination of these factors. There are two mechanisms by which eyestrain can be caused, one physiological and one perceptual. The physiological itself can take two forms, dryness of the surface of the eye and muscular strain in the oculomotor system, that is, in the muscle system that controls the accommodation and convergence of the eyes (Sheedy et al., 2003; Sheedy, 2007). The perceptual is the stress that is felt when the visual system has difficulty in achieving its primary aim, to make sense of the world around us. Conditions that call for prolonged near viewing or that require the oculomotor system to hold a fixed position for a long time or to make frequent movements of the same type are likely to produce eyestrain through muscular exhaustion. Conditions that make it difficult to see what needs to be seen or that distract attention from what needs to be seen are likely to produce eyestrain through stress. Lighting conditions that have been shown to lead to eyestrain are inadequate illuminance for the task (Simonson and Brozek, 1948), excessive luminance ratios between different elements of a task (Wibom and Carlsson, 1987), glare (Sheedy and Bailey, 1995) and lamp flicker, even when it is not visible (Wilkins et al., 1989). Despite this list, it is important to appreciate that in conditions where the task is visually easy and free from distraction or perceptual confusion, the visual system can function for many hours without eyestrain. Carmichael and Dearborn (1947) measured the eye movement patterns of people continuously reading books printed in high contrast, 10-point print, for 6 h, at an illuminance of 160 lx, expecting to find signs of eyestrain. No such signs were found. Apparently, the visual system is perfectly capable of prolonged activity without strain in the right conditions. Even when the conditions are not right, vision does not fail. Rather, it protests but will rapidly recover with rest.

14.3.2 Falls

Falls are a leading cause of trauma and a common harbinger of death among the elderly. To avoid falls, it is necessary for people to have good postural control. Information from the visual, proprioceptive and vestibular systems all affect postural control. The deterioration in these systems that occurs with age results in impaired postural control (Black and Wood, 2005). But what is the role of vision? Closing the eyes so no visual information is available reduces postural control as shown by increased body sway (Turano et al., 1994). Even when the eyes are open, people with vision loss show reduced postural stability (Anand et al., 2003; Lee and Scudds, 2003). More generally, postural stability is related to visual acuity and contrast sensitivity (Lord et al., 1991). From this, it might be thought that one solution to the problem of falls among the elderly would be to encourage lighting and décor suitable for the elderly (see Section 13.8). While this is correct for most of the day, there is one situation where such an approach is inappropriate – at night, when high light levels can interfere with sleep but the elderly regularly need to leave their bed to visit the bathroom. The usual way to deal with this dilemma is to provide a nightlight, this being a simple luminaire that provides a low level of diffuse ambient lighting. Figueiro et al. (2008b) examined the effect of enhanced visual information provided by a linear LED lighting system mounted around the frame of the bathroom door. Participants, who were all older than 65 years of age, sat on a chair facing the door. The linear LED lighting produced four different illuminances, 0.3, 1.0, 3.0 and 10 lx at the participants' eyes. Separately, a set of nightlights provided uniform ambient illumination giving 0.3 lx at the participants' eyes. The door and the attached linear LED lighting were aligned vertically and tilted 4.3° to the left or right. The participants were asked to stand up while looking at the door. Their postural control was measured in two ways, by the symmetry of weight carried on the left and right feet and by the sway velocity in degrees/second. For the left/right weight distribution, there was no statistically significant difference between the linear LED when vertical and the nightlight, but when the LED system was tilted to the left, the participants leaned to the left and when it was tilted to the right, they leaned to the right. For sway velocity, there was an interaction between the door tilt and the time of measurement, indicating that sway velocity was greater when the door was tilted but only for the first 2 s of movement. In a similar experiment, Figueiro et al. (2011) measured the walking characteristics of elderly people moving along a level path illuminated by conventional nightlights, with and without two horizontal laser beams defining the path. It was found that the presence of the horizontal laser beams resulted in faster walking with less variability in stride length by people at a high risk of falls, features associated with safer movement.

There are two implications of these results. The first is that visual information is important to postural stability. The second is that greater postural stability is achieved when the visual signal reinforces signals from other sensory systems rather than conflicting with them. In a sense, the use of vertical lighting on the doorframe and the horizontal laser beams along the path are examples of the principle of supplying high contrast on salient detail for people with vision loss (see Section 13.8)

14.3.3 Migraine

Everyone is likely to experience eyestrain in poor lighting conditions, but there are some groups who are particularly sensitive to lighting conditions. One such group is those who suffer from photoepilepsy (Fisher et al., 2005). Given fluctuating light of the right frequency, covering a large area and at a high percentage modulation, these individuals can be driven into a seizure. The frequency to which people with photoepilepsy are most sensitive is about 15 Hz, although about 50% still show signs of a photoconvulsive response at 50 Hz (Harding and Jeavons, 1995). Seizures start in the visual cortex and occur when normal physiological excitation involves more than a critical cortical area and are most likely when that cortical excitation is rhythmic (Wilkins, 1995).

A larger but related group who suffer adverse consequences from instability in light output are migraineurs. Migraine has been described as a neurovascular reaction to changes in the individual's internal or external environment. A migraine attack is much more than a severe headache. Nausea, vomiting, intolerance of smells and photophobia are all part of a migraine attack. The exact cause of a migraine is not known, but Wilkins (1995) speculates that cortical hyperexcitability linked to the magnocellular pathway is responsible for triggering a migraine attack. What is known is that light and lighting are common triggers of migraine (Shepherd, 2010) and that migraineurs are more sensitive to light than people who do not experience migraine, even when they are headache-free (Main et al., 1997). This means migraineurs are much more likely to experience glare from luminaires and to complain about high light levels. In addition, migraineurs are likely to be hypersensitive to visual instability, no matter whether it is produced by fluctuations in light output from a light source, or by large area, regular patterns of luminance (Marcus and Soso, 1989; Wilkins, 1995). Whether large area, high-contrast regular luminance patterns are present in an environment is usually the responsibility of the architect or interior designer because they decide on the decor, but the presence of light output fluctuations is the responsibility of the lighting designer. One way to ensure that light output fluctuations do not cause trouble is to use light sources that are inherently low in modulation, such as the incandescent lamp. If high modulation discharge light sources are to be used, they should be operated from high-frequency control gear. If LEDs are used, they should be operated from a very stable DC driver. Wilkins et al. (1989) carried out a field study in an office of the effect of replacing magnetic control gear operating from a 50 Hz electricity supply with electronic control gear operating at 32 kHz, on the frequency of headaches and eyestrain. The fluorescent lighting operating from the magnetic control gear had a modulation of about 45% at a fundamental frequency of 100 Hz. The same lamps operating from the electronic control gear had a modulation of less than 7% at 100 Hz. Figure 14.4 shows the percentage of the occupants experiencing various frequencies of headaches per week when working under the two types of fluorescent lighting. The distribution of headaches per week is strongly skewed. This implies that everybody in the office gets a headache now and again, for all sorts of reasons, but there a few people who experience headaches two or three times a week. Figure 14.4 demonstrates that changing from magnetic to electronic control gear does little for the mass of people but does help the people who frequently have headaches. With the electronic control gear, nobody had a headache more frequently than 1.3 times/week. A similar change occurred in the distribution of the frequency of eyestrain per week. Kuller and Laike (1998) report a similar pattern in that individuals who had a high critical flicker frequency showed an increased arousal of the central nervous system when working under lighting controlled from conventional magnetic (50 Hz) control gear.

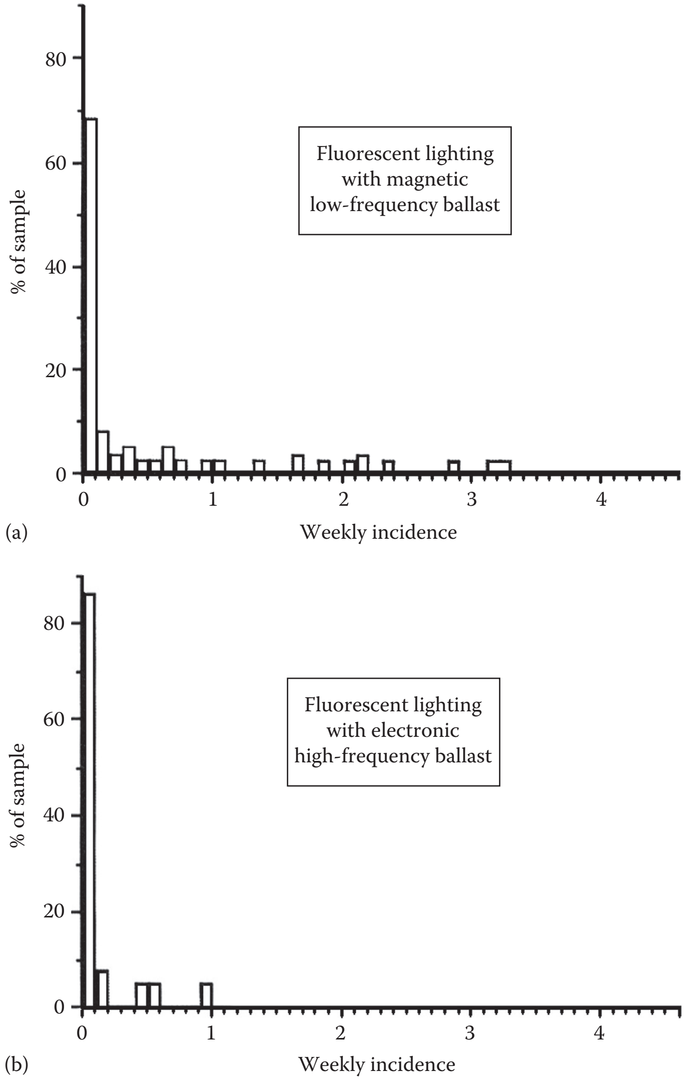


FIGURE 14.4 Percentage of a sample of office workers experiencing different frequencies of headaches per week while working under fluorescent lighting operated on (a) magnetic (50 Hz) control gear and (b) electronic (32 kHz) control gear. (After Wilkins, A.J. et al., *Lighting Res. Technol.*, 21, 11, 1989.)

14.3.4 Autism

Another group who can be expected to be sensitive to fluctuations in light output are the autistics. Autism is a neurological disorder that affects a child's ability to communicate, understand language, play and relate to others. Symptoms are repetitive activities, stereotyped movements and resistance to changes in the environment and the daily routine and unusual responses to sensory experiences. The level of arousal of autistic children is chronically high, and repetitive behaviours are believed to be a way of regulating it (Hutt et al., 1964). This implies that an increase in environmental stimulation will generate an increase in repetitive behaviour, and regular fluctuations in light output can be regarded as a form of environmental stimulation. Observations of autistic children have demonstrated that repetitive behaviour does occur more frequently under fluorescent lighting than under incandescent lighting (Colman et al., 1976; Fenton and Penney, 1985). This suggests that autistics too would benefit from the use of electronic control gear for fluorescent lamps and very stable drivers for LEDs. Care should also be taken to avoid lighting control systems that change light levels suddenly.

14.4 LIGHT OPERATING THROUGH THE CIRCADIAN TIMING SYSTEM

The circadian timing system is fundamental to the functioning of many processes in life, and a regular cycle of exposure to light and darkness is important for its entrainment. Therefore, it should not be too surprising that light operating through the circadian timing system has a number of impacts on human health. This is most evident in people who undertake sustained night-shift work, particularly where a rapidly rotating shift system is used so that they never fully adjust their circadian cycle (Schernhammer and Thompson, 2011). Such shift work is associated with frequent circadian disruption which, in turn, is associated with an enhanced risk of major health hazards such as heart disease, cancer and diabetes (Knutsson, 2003), often leading to an early death (Knutsson et al., 2004).

14.4.1 Sleep

The sleep–wake cycle is one of the most obvious and important of the circadian rhythms. Poor-quality sleep and sleep deprivation are linked with failures of memory, worse coordination and deterioration in cognitive function, all effects that can lead to an increased number of accidents and reduced productivity (Lockley et al., 2007; Rosekind et al., 2010). There are a number of common sleep disorders. Those susceptible to treatment with light are concerned with the timing and duration of sleep. Those associated with timing are delayed and advanced sleep phase disorders. Delayed phase sleep phase disorder is characterized by late sleep onset and late awakening and is predominantly experienced by young people. Delayed sleep phase disorder need not necessarily cause a problem, provided sleep duration is normal and the individual can adjust his/her work and social schedules to his/her sleep pattern. However, if sleep duration is reduced and/or the timing of sleep is inconsistent with such societal requirements as being at work at a fixed time, then chronic sleep debt is likely. People with chronic sleep debt feel permanently tired.

Advanced phase sleep disorder is characterized by early sleep onset and early morning awakening and is predominantly experienced by the elderly. Again, advanced sleep phase disorder may not cause a problem as long as the duration of sleep is normal and the individual's lifestyle can be adjusted to accommodate it.

Exposure to light has been shown to be an effective treatment for these sleep disorders. Czeisler et al. (1988b) have demonstrated that exposure to 10,000 lx at appropriate times results in significant phase advances for people with delayed sleep phase disorder and significant phase delays for those with advanced sleep phase disorder. As would be expected from the human phase response curve (see Section 3.4.1), the appropriate times are immediately on awakening for the delayed sleep phase disorder and in the evening for the advanced sleep phase disorder.

As for sleep duration disorders, the classic problems are sleep onset insomnia with normal awakening and normal sleep onset with sleep maintenance insomnia. Both these disorders are common in the elderly (Campbell and Dawson, 1991; Foley et al., 1995). Lack and Schumacher (1993) have shown that exposure to bright light in the evening produces longer and better quality sleep for people who were experiencing sleep maintenance insomnia.

There can be little doubt that exposure to enough light at the right time is helpful in promoting sleep, but what is enough light, how long should exposure last and what spectrum should the light have? Unfortunately, there are no clear answers to these questions. A wide range of illuminances at the eye, from 2,500 to 10,000 lx, and a wide range of electric light source types, from standard fluorescent lamps to blue LEDs, have been shown to be effective in the treatment of sleep disorders (Terman et al., 1995; Gooley, 2008). Such high illuminances are unrealistic for conventional building lighting but may well be the result of a desire to guarantee a beneficial effect. Given that what is required is to provide an effective light stimulus to the melatonin-based circadian system, it seems reasonable to suppose that by matching the spectral emission of the light source to the spectral sensitivity of this circadian timing system, and by administering the dose at the most time-sensitive period of the day, such as at dawn and dusk, a much lower illuminance could be used. However, all this manipulation may be unnecessary. The spectral content of daylight is well suited to stimulate both the visual and the circadian timing system. Both have evolved under a natural regime of daylight days and dark nights. The alternative electric light sources have only been available for use by day and night for about a hundred years, a very short time in evolutionary terms. It may be that the main impact of a greater understanding of the role of light exposure on the circadian system will be to return attention to the better daylighting of buildings (CIE, 2004e).

14.4.2 Seasonally Affective Disorder

Depression is one of the most common psychiatric conditions in patients visiting a doctor, with a lifetime prevalence of about 17% (Kessler et al., 1994). Seasonally affective disorder (SAD) is a subtype of major depression that is identified by a regular relationship between the onset of depression and the time of year, full remission of depression at another time of year, the pattern of onset and remission of depression at specific times of the year repeated over the last 2 years, no non-seasonal depression over the last 2 years and episodes of seasonal depression substantially outnumbering nonseasonal depression over the individual's lifetime (American Psychiatric Association, 2000). Two forms of SAD have been identified, winter and summer SAD, the former being much more common than the latter. Winter SAD can be recognized by the increase in feelings of depression and a reduced interest in all or most activities, typical of depression, together with such atypical symptoms as increased sleep, increased irritability and increased appetite with carbohydrate cravings and consequent weight gain. These symptoms disappear in summer. Summer SAD is also associated with an increase in feelings of depression and lack of interest in activities, but in this case, there is a decrease in sleep, poor appetite and weight loss (Wehr et al., 1991). Winter SAD is experienced by about 5% of the population of the United States and about 10%–20% have subsyndromal symptoms, the percentages increasing with an increase in latitude (Kasper et al., 1989b; Wehr and Rosenthal, 1989; Rosen et al., 1990). The prevalence of winter SAD increases with age until about the sixth decade, after which it declines dramatically.

The proposed basis of SAD is circadian misalignment, symptoms being reduced as circadian misalignment is reduced (Lewy et al., 2006, 2007). This is consistent with the finding that exposure to bright light is often an effective treatment for SAD (Golden et al., 2005; Lam et al., 2006; Ravindran et al., 2009). What is meant by bright light is usually exposure to a light box that produces an illuminance at the eye of between 2,500 and 10,000 lx. Exposure durations range from 30 min for 10,000 lx to 2 h for 2,500 lx, usually in the morning, although the exact timing of the exposure to bright light is relatively unimportant (Wirz-Justice et al., 1993). At these illuminances, the specific light spectrum is also not important, although there is no doubt that shorter wavelengths are more effective than longer wavelengths (Lee et al., 1997). The fluorescent lamp is the light source most commonly used in light boxes, mainly because of its high luminous efficacy and large surface area. The latter makes it easier to provide the required illuminance from a large area source so that visual discomfort is less than would be the case for the same illuminance provided by a point source. A good light box will also have a filter to stop UV radiation being emitted.

Response to bright light can usually be expected within 2–4 days, and a measurable improvement is often seen within 1 week, but symptoms will reappear if light treatment is discontinued. The symptoms that are atypical of depression in general are the ones that are most responsive to light treatment, that is, hypersomnia, increased appetite and carbohydrate cravings. As with most medical treatments, there are side effects of prolonged exposure to the high illuminances of a light box. Typically, they are mild disturbances of vision and headaches that subside with time. However, care should be taken with patients who have a tendency towards mania or whose skin is photosensitive or who already have retinal damage or who have a medical condition that makes retinal damage likely (Levitt et al., 1993; Gallin et al., 1995; Kogan and Guilford, 1998). General guidance on the use of light in the treatment of SAD is available from a number of sources (Lam, 1998; Saeed and Bruce, 1998; Lam and Levitt, 1999). Measurements of the optical radiation safety of the lamps commonly used for treating SAD indicate that they do not pose a hazard (Baczynska and Price, 2013).

14.4.3 Alzheimer's Disease

Alzheimer's disease is a degenerative disease of the brain and is the most common cause of dementia. It first becomes evident to the external observer when the individual starts forgetting recent events or familiar tasks. As it develops, memory loss becomes more global, accompanied by personality change and reduced communication. It leads, eventually, to a complete unawareness of the world. The effect of these changes is to destroy the individual's personality and leave behind an empty shell. Lighting can influence the abilities and behaviour of people with Alzheimer's disease, operating through both the visual system and the circadian timing system. Alzheimer's patients show a reduced contrast sensitivity function relative to healthy people of the same age (Gilmore and Whitehouse, 1995) (Figure 14.5). This pattern of change is consistent with the reports of cell loss at both retinal and cortical level in Alzheimer's disease, particularly for the magnocellular channel of vision (Blanks et al., 1991; Hof and Morrison, 1991; Kurylo et al., 1991). It has been argued that such reduced visual capabilities may exacerbate the effects of other cognitive losses in Alzheimer's patients, tending to increase confusion and social isolation (Mendez et al., 1990; Uhlman et al., 1991). This suggests that enhancing the luminance contrast of the stimulus would improve the functioning of Alzheimer's patients. Gilmore et al. (1996) have shown that increasing the luminance contrast does increase the speed of letter recognition by Alzheimer's patients (Figure 14.6). This finding, suggesting as it does that Alzheimer's patients are struggling to make sense of the world with diminished visual and cognitive capabilities, raises the intriguing possibility that lighting designed to enhance the capabilities of people with vision loss might also be effective in helping people with Alzheimer's disease (see Section 13.8). This is a possibility that deserves investigation.

As for the circadian timing system, people with Alzheimer's disease and other forms of dementia often demonstrate fragmented rest/activity patterns throughout the day and night (Aharon-Peretz et al., 1991; van Someren et al., 1996). This makes such patients difficult to care for and is one of the main reasons for having them

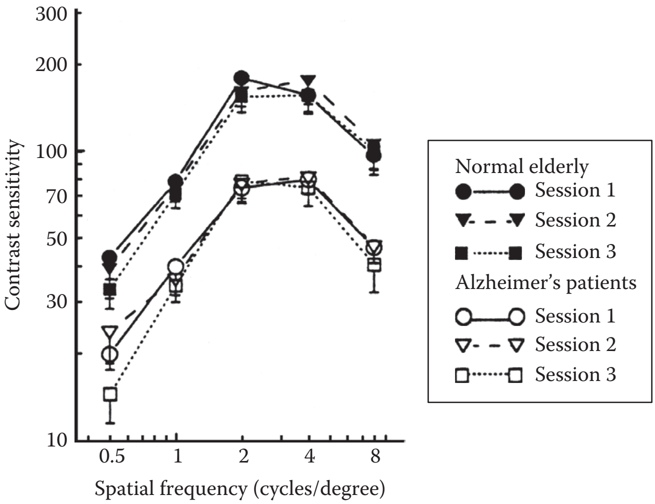


FIGURE 14.5 Contrast sensitivity functions for the healthy elderly and the elderly with Alzheimer's disease, measured at three different times in 1 year. (After Gilmore, G.C. and Whitehouse, P.J., *Optom. Vis. Sci.*, 72, 83, 1995.)

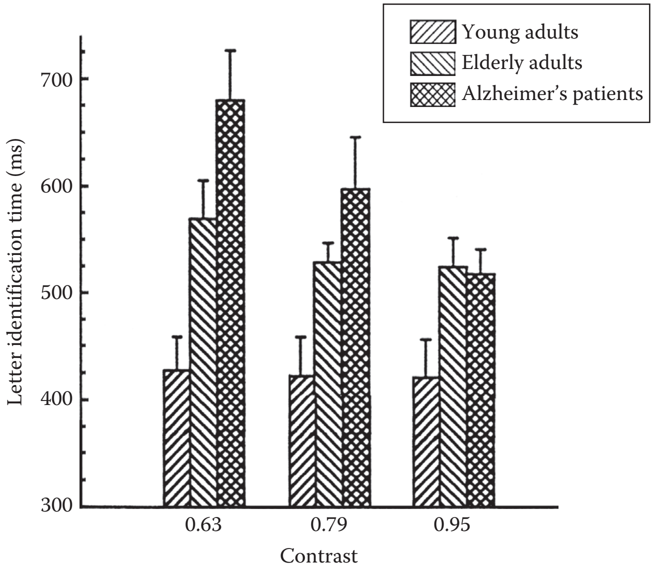


FIGURE 14.6 Mean time taken to identify individual letters by young, healthy adults, elderly, healthy adults and elderly, adults with Alzheimer's disease, at letter luminance contrasts of 0.63, 0.79 and 0.95. (After Gilmore, G.C. et al., *J. Clin. Geropsychol.*, 2, 307, 1996.)

institutionalized (Pollak and Perlick, 1991). The circadian timing system is controlled by the suprachiasmatic nucleus (SCN), which in turn are entrained by exposure to alternate periods of light and dark (see Section 3.3.2). Degeneration is evident in the SCNs of people with Alzheimer's disease (Swaab et al., 1985), and such patients are less likely to be exposed to bright light (Campbell et al., 1988). This suggests that exposing Alzheimer's patients to bright light during the day and little light at night, thereby increasing the signal strength for entrainment, would help to make their rest–activity patterns more stable. Studies using light boxes of the type used for the treatment of SAD have been used to demonstrate such benefits (Lovell et al., 1995). Specifically, patients were placed in front of a light box producing 1500–3000 lx at the eyes for 2 h during the day. The result was reduced agitation and wandering at night and more stable rest/activity rhythms. Unfortunately, Alzheimer's patients are not the most compliant as regards instructions, so continuous supervision is necessary to keep the patient in front of the light box. A more practical alternative is to increase the general illuminance in rooms where patients spend their days to a high level. Van Someren et al. (1997b) tested this approach using 22 institutionalized patients with various forms of dementia. The average illuminance on the eyes of these patients when in their living rooms was increased from 436 to 1136 lx by changing the lighting installation. After 4 weeks, the installation was returned to its original state, the resulting average illuminance being 372 lx (the values are different because the lighting includes a daylight component). Figure 14.7 shows the raw hourly activity data for a patient with Alzheimer's disease. It also shows two cycles of the average and associated standard deviation of the 24 h activity level for all patients for the three lighting conditions. The longer and lower average level

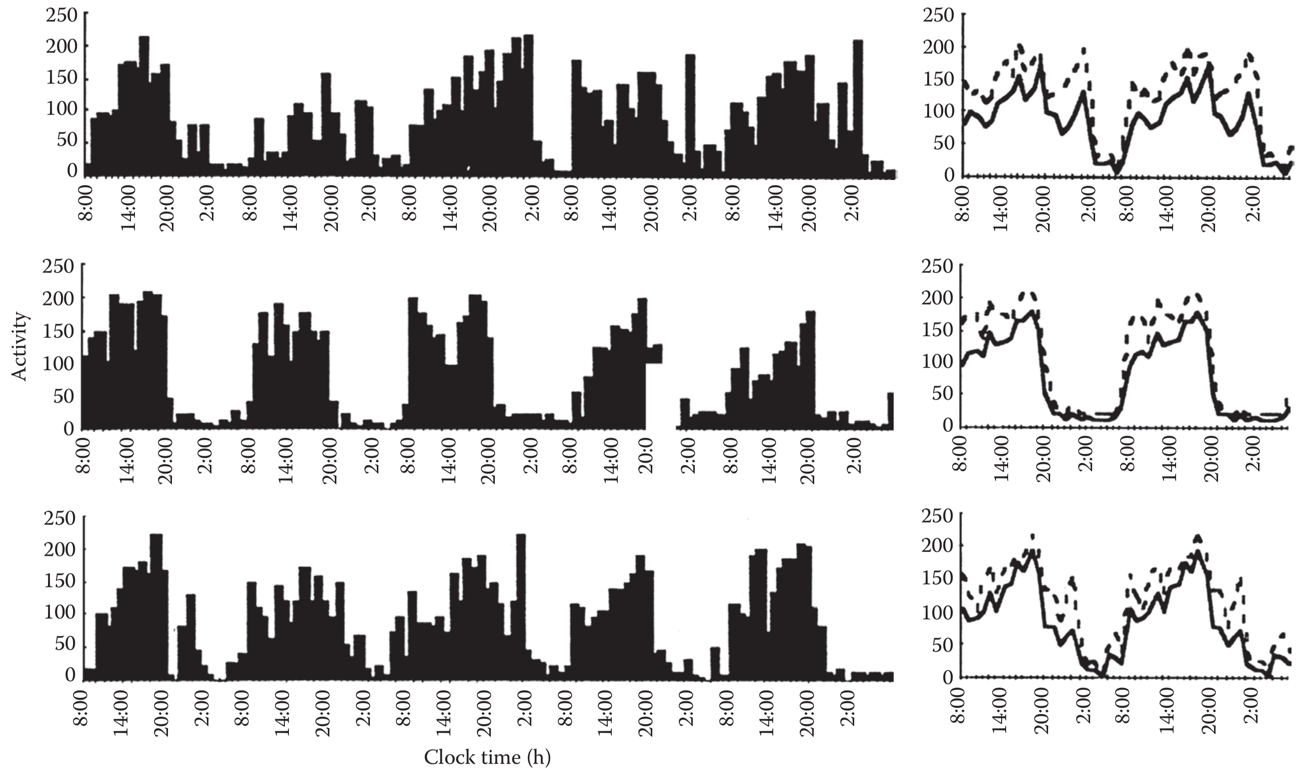


FIGURE 14.7 The left panels show the raw hourly activity data of a patient with Alzheimer's disease over 5 days, before (upper panel), during (middle panel) and after (lower panel) bright light treatment. The right panels show two cycles of the average activity level (solid line) and the associated standard deviation (dashed line) over 24 h for 22 subjects with various forms of dementia for the same light exposure conditions. (After van Someren, E.J.W. et al., *Biol. Psychiatry*, 41, 955, 1997b.)

of activity and the reduced variability at night when the patients were exposed to bright light during the day is obvious. Further, a careful regression analysis of the data showed that patients with severe vision loss did not benefit from exposure to bright light, suggesting that the bright light is not acting as a placebo. There can be little doubt that lighting has a role to play in the management of Alzheimer's patients and maybe that of patients with other forms of dementia. Interestingly, a large-scale study by Riemersma-van der Lek et al. (2008) has shown that exposure to bright light during the day can slow the rate of deterioration of people with dementia. Similarly, Royer et al. (2012) have shown that exposure to 400 lx of short-wavelength light for 30 min a day improved the cognitive functioning of elderly people in long-term care. Whether such improvements are a direct result of higher illuminances during the day increasing alertness or an indirect result of better sleep at night or both has yet to be determined. Nonetheless, recommendations for the lighting of the homes of people with dementia have been published (Torrington and Tregenza, 2007).

14.5 UNRESOLVED ISSUES

There are a number of unresolved issues related to the impact of light exposure on human health. They include the possibility that exposure to light at night is involved in the development of various forms of cancer, the extent to which many people are vitamin D deficient, whether or not there is a minimum amount of light that people need to receive every day for good mental health, the effect of daylight on recovery from surgery and the possibility that exposure to short wavelength light may be involved in the development of macular degeneration. These issues are unresolved for three reasons. The first is because, although there is epidemiological evidence for an effect of light, the exact mechanism is not understood. The second is that there is a conflict between advocates because what is required to alleviate one condition is believed to worsen another. The third is that the benefit of the treatment is uncertain but the cost is sure.

14.5.1 Cancer

One unresolved health issue is the possible link between light exposure and the development and growth of cancers and neurodegenerative diseases (Reiter, 2002; Stevens et al., 2007; Stevens, 2009). Breast cancer has been the most widely studied form of these. The incidence of breast cancer has increased continuously since the turn of the twentieth century in industrialized societies, a development that coincides with the growth in the use of lighting (Chu et al., 1996). In 1987, it was suggested that this increase could be at least partly ascribed to the suppression of melatonin following exposure to light at night when melatonin concentration is high (Stevens, 1987). Evidence for this possibility comes in two forms, epidemiology and basic physiology. Epidemiological studies have shown that female night-shift workers are at greater risk of breast cancer than females who work during the day (Megdal et al., 2005). There is also evidence that females who are blind have a lower probability of breast cancer (Flynn-Evans et al., 2009). As for the basic physiology, studies have shown that suppression of melatonin by light exposure can increase the rate of tumour growth (Jasser et al., 2006). There is growing acceptance of the hypothesis that repeated exposure to sufficient light to suppress melatonin from its normal concentration has some role to play in the incidence and development of breast cancer, but there may be other necessary conditions yet to be established (Figueiro et al., 2006, Schernhammer et al., 2006). Also, whether the role of light exposure is primarily due to acute suppression of melatonin or chronic circadian disruption remains an open question.

The implications of the possible role of light exposure in cancer for the lighting of buildings at night are mixed. Assuming that melatonin suppression is necessary for any adverse effects to occur and that the threshold for melatonin suppression using incandescent lamps is about 30 lx at the eye for 30 min (Figueiro et al., 2006), the amount of light present when people are trying to sleep or when briefly visiting the bathroom at night should not be a problem. However, the illuminances provided in commercial and industrial premises for vision and where people are working for many hours with melatonin levels suppressed should be a cause for concern. This is often the case for people working night shift. One approach to reducing the risk of light exposure at night, which is when people should have a high melatonin concentration, is to use a light spectrum with little short-wavelength and a lot of long-wavelength radiation. This spectrum will not suppress melatonin and may enhance alertness. It is also worth noting that there are a number of sources of light other than lighting that may represent a hazard. For example, computer screens, televisions and other display screens can emit large amounts of short-wavelength light. When considering the actual light exposure at night, it is important to consider all sources of light to which people may be exposed and the intensity, spectrum, timing and duration of exposure at the eye.

14.5.2 Vitamin D Deficiency

Vitamin D is an essential nutrient for regulating calcium uptake. Adequate levels of vitamin D are necessary to maintain strong bones and teeth. Inadequate levels of vitamin D lead to bone-softening diseases such as rickets in children and osteomalacia in adults. More recently, a role for vitamin D in regulating the immune system, and in the prevention of some cancers, diabetes and hypertension, has been identified (Webb, 2006; Holick, 2007). Inadequate levels of vitamin D have also been associated with several psychiatric disorders, most notably depression, anxiety and schizophrenia (Berk et al., 2009).

Vitamin D is synthesized in the skin when exposed to UV radiation between 290 and 330 nm. This range overlaps with the action spectrum for erythema (Figure 14.1). Consequently, there is considerable argument about the necessary level of exposure to UV radiation, one side emphasizing the benefits of vitamin D and the other the risks of erythema (Vieth et al., 2007; McKenzie et al., 2009). No one recommends adding a UV component to the spectrum of interior light sources. What is recommended is that some exposure to UV radiation outdoors occurs. It is thought that adequate sunlight exposure to provide for healthy vitamin D levels for a light-skinned person is approximately 15 min exposure (without sunscreen) to the face and arms, around midday, although longer times will be required for those with very dark skin. However, this action is not possible in all countries. Because of absorption in the atmosphere, sunlight can only generate vitamin D when the sun is high in the sky. Thus, people living in high latitudes are unable to synthesize vitamin D in the skin during the winter months, regardless of the duration of time they spend outdoors. Further, a lot of people at all latitudes spend a lot of their time indoors, so it is not surprising that the prevalence of low levels of vitamin D is high (Hyppönen and Power, 2007; Gozdzik et al., 2008). According to one calculation, 10% of Canadians have insufficient vitamin D for good bone health (Langlois et al., 2010). The Canadian Cancer Society recommends adults to take vitamin D supplements daily during the winter months.

14.5.3 Adequate Light Dose

Light exposure monitoring has revealed that the total daily light exposure of many people is low. One study conducted in San Diego during a temperate and sunny period showed that people spent most of their time indoors (Espiritu et al., 1994). When awake, the median person spent more than 50% of the time in illuminances below 100 lx and only 4% of each 24 h in illuminances greater than 1000 lx. A similar pattern has been found at the higher latitude of Montreal in summer with even less exposure in winter (Hébert et al., 1998). Exposure matters because there is evidence that increasing light exposure improves mood. In the San Diego study, the people with the shortest daily exposure time to high light levels reported the lowest mood (Espiritu et al., 1994). A large study in Finland found that health-related quality of life was higher for people reporting higher interior light levels (Grimaldi et al., 2008), while in California, a study of 200 office workers found that those with the most daylight illumination at their desks or the largest window views to the outside had the fewest complaints of headaches and fatigue and the fewest complaints about other environmental discomforts (Heschong Mahone Group, 2003a).

Such studies reveal correlations not causations; they cannot say whether low light exposure causes lower moods or whether people with more depressive symptoms are less likely to expose themselves to higher light levels. However, experimental studies undertaken in Finland during winter months provide stronger evidence for the benefits of increasing daytime light exposure, even among healthy adults. In three of these experiments, daily light exposure was increased by adding supplemental lighting to a gymnasium visited by some of the participants for 1 h, three times per week. The supplementary lighting raised the horizontal illuminance to 2400–4000 lx. The rest of the gym lighting remained at its usual 400–600 lx. All the participants increased their physical fitness following the exercise regimen, but those in the brighter gym reported improvements in feelings of vitality and reductions in atypical depression symptoms (Partonen et al., 1998; Leppämäki et al., 2002a,b). Another experiment involved giving participants a light box to use for an hour daily, usually at their workplaces. Mood improvements were noted during the weeks when the light boxes were used, but the effects disappeared during weeks when they were not in use (Partonen and Lönnqvist, 2000).

These findings, among others, led the CIE to conclude that the daily light dose received by people in industrialized societies might be too low for good mental health (CIE, 2004e). The key word here is might. It is certainly possible because serotonin influences mood, and exposure to 2000 lx has been found to increase the uptake of tryptophan, an amino acid from which the body manufactures serotonin (aan het Rot et al., 2007). However, at the moment, there are more questions than answers to this possibility (Brainard and Veitch, 2007). We are a long way from knowing the necessary light levels for the desired effects or the necessary duration or timing of these exposures, but this has not stopped the marketing of light sources claiming to provide such benefits.

There are two concerns about the suggestion that daily light exposures should be increased. One is the energy and environmental costs of doing so if electric lighting is used. Fortunately, more daylight and sunlight inside buildings is one means to achieve an increase in light exposure without necessarily incurring such costs (CIE, 2004e; Noell-Waggoner, 2006). The other is the view that exposure to light, particularly short-wavelength light, has a cumulative toxic effect on the eye that may lead to an increased risk of macular degeneration in old age (Margrain et al., 2004). A counterview is that greater exposure to short-wavelength light is necessary in old age to offset the increased yellowing of the lens so as to maintain effective operation of the circadian timing system (Turner et al., 2010). The balance between these various outcomes of light exposure has yet to be identified.

14.5.4 Recovery from Surgery

An area of increasing interest in the field of light and health is the impact of daylight exposure on recovery from surgery. Work has been reported on the outcomes of hospital treatment following myocardial infarction (Beauchemin and Hays, 1998), the use of painkillers following spinal surgery (Walch et al., 2005) and the length of stay in hospital following various types of medical procedure (Choi et al., 2012; Joarder and Price, 2013). In all cases, the effect reported is that being exposed to more daylight and, in some cases, sunlight leads to faster and easier recovery. The problem with these studies is that there is no established explanation for these results. Exposure to daylight may or may not be the true cause of the faster and easier recovery. Daylight is usually delivered through windows, which means that receiving daylight is confounded with having a view-out. Some people argue that it is the psychological effect of the view-out that matters, while others believe that it is the physiological impact of daylight or sunlight that is important. If it is the view-out that matters, the question of what sort of view arises. It seems reasonable to assume that a view of a pleasant natural scene with some activity would have a more positive effect than a view of the hospital mortuary. Certainly, Moore (1981) found that prisoners whose windows looked out over hills and farmland made significantly fewer sick calls to the prison infirmary than those whose windows overlooked the prison yard, and Ulrich (1984) found that patients whose rooms afforded a view of the natural landscape rather than of other buildings spent fewer days in hospital. If it is the actual daylight or sunlight exposure that matters, then how much daylight is required and how it should be timed remain to be determined. Of course, it may be that daylight is simply a convenient way to deliver an adequate light dose at an appropriate time. This is certainly the belief behind commercial lighting systems designed for use in patient rooms that use electric lighting to simulate the natural variation of light.

14.5.5 Short-Wavelength Light and Macular Degeneration

It has long been known that exposure to light, particularly short-wavelength light, can damage the retina (Ham et al., 1976). The eye has a number of mechanisms for limiting such damage, but as the eye ages, these mechanisms become less effective, although it can be argued that the yellowing of the lens with age provides some protection (Blackmore-Wright and Eperjesi, 2012). Elderly people with cataract routinely have their lens removed and replaced with a clear plastic lens. While this certainly produces vast improvements in visual function, there is concern that the consequent increase in short-wavelength light represents an increased risk of macular degeneration occurring. As a result, intraocular lenses are available that filter light below about 500 nm, that is, blue-filtering intraocular lenses. The value of these is a subject of controversy. Some argue that there is no epidemiological evidence that exposure to light is associated with macular degeneration and that with the blue-filtering intraocular lens, there is a risk of reducing the stimulation of the circadian timing system and of causing a deterioration of visual function at low light levels (Turner et al., 2010). Others argue that studies comparing intraocular lenses with and without blue-light filtering show little difference in visual functions (Davison et al., 2011). Yet others have examined the effect of blue-filtering intraocular lenses on sleep quality and found no adverse effects (Landers et al., 2009). No doubt, this is an argument that will continue for some time, but it may be a distraction from the real problem. Berman and Clear (2013) have calculated that although light sources with a lot of short-wavelength light are more hazardous than those with less, the effect of spectral power distribution is overwhelmed by those of dose when people go outside for even a short time because daylight is rich in short wavelengths and provides a lot of light at the eye. This suggests that those who wish to reduce the risk of macular degeneration in the general population should focus their attention on limiting exposure to the high light levels provided by daylight.

14.6 SUMMARY

Exposure to light can have both positive and negative impacts on human health, impacts that can become evident soon after exposure or only after many years. The effects of light on health can be conveniently arranged in four classes. The first class is that of light treated as radiation. For this class, the definition of light is stretched to include UV and IR radiation as well as visible radiation, because many light sources produce all three types. In sufficient doses, exposure to light can cause damage to both the eye and skin, through both thermal and photochemical mechanisms. In the short term, UV radiation can cause photokeratitis of the eye and erythema of the skin. Prolonged exposure to UV radiation can lead to cataract in the lens as well as skin aging and skin cancer. Visible radiation can produce photoretinitis of the retina. Visible and short-wavelength IR radiation can cause thermal damage to the retina and burns to the skin. Prolonged exposure to IR radiation can lead to cataract and burns. Guidance setting out the threshold limit values and the associated maximum permissible exposure times that should be observed to avoid these detrimental effects on health, and a lamp hazard classification system based on these threshold limit values, is available. When evaluated using these methods, most light sources used for general lighting pose no hazard to health, but a few do. The most hazardous light source to which most people are exposed is the sun.

The threshold limit values assume a normal response, but there are some groups who are much more sensitive to light as radiation than the normal population. Among such groups are the newborn, aphakics and people taking certain pharmaceuticals. All these effects of light as radiation are negative, but light as radiation can also have positive effects on health. Specifically, controlled exposure to light of particular wavelengths can be used as a treatment for hyperbilirubinemia, some skin disorders, some tumours and an overactive immune system. It can also be used as a means of limiting the spread of airborne diseases, such as tuberculosis, through its ability to deactivate pathogens.

The second class is light operating through the visual system. Lighting conditions that cause visual discomfort are likely to lead to eyestrain, and anyone who frequently experiences eyestrain is not enjoying the best of health. The lighting conditions that cause visual discomfort are well known and easily avoided. Some people have medical conditions that make them especially sensitive to lighting conditions. Migraineurs and autistics are two such groups. Both are sensitive to the temporal modulation of light. There are also indirect effects of lighting on health to be considered. One common problem is the risk of falls among the elderly when moving about at night. Lighting that reinforces signals from other senses has been shown to lead to better balance.

The third class is light operating through the circadian timing system. The sleep–wake cycle is one of the most obvious circadian rhythms, so it is hardly surprising that exposure to bright light at the right time can be used to treat some sleep disorders involving the timing and duration of sleep. Exposure to bright light is also a useful means of stabilizing the rest–activity cycle of people with Alzheimer's disease and of relieving the symptoms of seasonal affective disorder.

The fourth class consists of a number of unresolved issues. These issues are unresolved because there is some doubt about the observed influence of light on the specific condition and also because there is no accepted explanation for the effect observed or because the conditions necessary to achieve the desired effect conflict with some other requirement. The unresolved issues include exposure to light at night and the incidence of cancer, the use of light to generate vitamin D, the need for a minimum light dose, the benefit of exposure to daylight on recovery from surgery and the role of exposure to blue light in the incidence of macular degeneration.

Clearly, there is still much to learn about the effects of light on human health, but what is known is enough to suggest the lighting of buildings should no longer be considered solely in terms of the effects on vision. In many ways, light is like fire, a good servant but a poor master. Exposure to light is essential for the visual system to operate, desirable for entraining the circadian timing system and valuable for the treatment of some medical conditions, but too much of the wrong wavelengths for too long and damage or injury may occur. It behoves anyone who is involved in the design and specification of lighting systems to be aware of these impacts of light on human health.

15 Light Pollution

15.1 INTRODUCTION

The provision of electric lighting is not without consequences for the environment. Electricity generation always causes pollution of the environment, either directly, as in air pollution caused by the burning of fossil fuels, or indirectly, when generating and transmission equipment has to be scrapped. But light itself can also be considered a form of pollution. Indeed, over the last two decades, public concern over the consequences of the use of light outdoors at night has been growing, driven by well-orchestrated advocacy campaigns using such emotive slogans as 'Our children will never see the stars'. As a result, there have been moves by governments in a number of countries to limit the use of light outdoors at night by regulation or legislation. This chapter is concerned with the origins of, consequences of, reactions to and measures against light pollution.

15.2 FORMS OF LIGHT POLLUTION

Light pollution, or obtrusive light as it is sometimes euphemistically called, can take three forms. These are sky glow, light trespass and glare. Sky glow refers to the increase in the luminance of the sky at night above that produced by natural sources such as moonlight. Sky glow is evident over most cities and towns in the form of a glowing, flattened dome of light (Figure 15.1).

Unlike sky glow, light trespass is a local phenomenon that causes disturbance to individuals. The classic event that provokes a complaint of light trespass is when light from a nearby luminaire enters a bedroom window (Figure 15.2). This is so common that manufacturers of street lighting luminaires usually offer a baffle, called a house side shield, as an optional extra. The feature that defines light trespass is when a significant amount of light crosses a property boundary and impacts the ability of the property owner to enjoy, in the legal sense, the use of that property.

Glare comes in two main forms, disability and discomfort glare (see Section 5.4.2) (Figure 15.3). Disability glare has an effect on visual capabilities that can be measured with conventional psychophysical procedures and a plausible mechanism, light scatter in the eye. Discomfort glare is not well understood. It occurs when people complain about visual discomfort in the presence of bright luminaires or windows. The characteristic that separates glare from light trespass is that glare causes discomfort, whereas light trespass causes disruption. Also, glare can be associated with high-luminance luminaires at a distance far enough away that the illuminance crossing the property boundary is very small so light trespass is negligible.

FIGURE 15.1 Sky glow above Canterbury, United Kingdom, population 149,000.

FIGURE 15.2 A classic light trespass situation. In this case, light trespass has been diminished by fitting the nearest luminaire with an internal house side shield. The house side shield can be seen in the image of the luminaire reflected in the bedroom window.

FIGURE 15.3 Disability and discomfort glare being produced by the building mounted floodlighting of an open car park.

15.3 CAUSES OF LIGHT POLLUTION

15.3.1 Sky Glow

Sky glow represents an increase in the luminance of the sky after dark caused by human activity, usually electric lighting. The baseline against which sky glow is measured is the sky luminance produced by light from the sun, moon, planets and stars, being scattered by interplanetary dust, and by molecules and aerosols in the Earth's atmosphere. In addition, there is a small contribution from light produced by a chemical reaction of the upper atmosphere with UV radiation from the sun. This sky luminance at zenith, after dark, is of the order of 0.0002 cd/m^2.

When light traverses the atmosphere, it is scattered by the air molecules and aerosols therein. Aerosols are suspended water droplets and dust particles. Air molecules scatter light forward and back with a little to the side. This Rayleigh scattering is much greater for short visible wavelengths, which is why the sky appears blue during the day. Aerosols scatter light predominantly forward. This Mie scattering is independent of wavelength in the visible region, which is why clouds appear white during the day. Where there are few aerosols and few air molecules, there is very little sky glow which is why major new optical telescopes are built in such areas as the Atacama Desert of the Chilean Andes, where the population is small, the air pollution is negligible and the air is very thin and dry.

One approach to assessing the magnitude of sky glow at a specific site is the Bortle Dark-Sky Scale (Bortle, 2001). This is an empirical nine-class scale in which a site is assigned to a class based on what an observer at the site can see in the sky, at the horizon and on the ground. It ranges from class 1 (excellent dark-sky site) to class 9 (inner-city sky). It is analogous to the Beaufort scale used for wind velocity. As such, it is a convenient method by which sky glow maps can be constructed and good sites for observing the heavens identified. However, it is not much use for predicting the effect of proposed lighting installations on sky glow. To do this, a quantitative model of sky luminance is required. There are a number of such models. One of the earliest and certainly the simplest is Walker's law (Walker, 1977). This can be stated as

$$I = 0.01Pd^{-2.5}$$

where

I is the proportional increase in sky luminance relative to the natural sky luminance, for viewing 45° above the horizon in the direction of a town or city
P is the population of the town or city
d is the distance from the viewing position to the town or city (km)

This empirical formula assumes a certain use of light per head of population. Experience suggests the predictions are reasonable for cities where the number of lumens per person is between 500 and 1000 lm. More sophisticated models based on the physics of light scatter have been used to generate sky glow maps (Baddiley and Webster, 2007; Kocifaj, 2007). These models enable predictions to be made for different altitudes and azimuths of viewing and different atmospheric conditions.

One aspect of sky glow that is often claimed to be of critical importance is light emitted from a luminaire close to the horizontal. This is certainly true for anyone hoping to see the stars from an observatory some distance from the nearest city or town, but it is not true for anyone in the town or city. For light to decrease the visibility of a star as seen from a fixed position, that light has to be scattered down the direct path from the point of observation to the star. If the point of observation is several miles from the main source of light, then obviously light emitted close to the horizontal has a better chance of intersecting the direct path than light emitted directly upwards. Further, light emitted close to the horizontal has to pass through an atmosphere containing many more air molecules and aerosols than the atmosphere at higher elevations. However, for someone in the town or city, light emitted close to the horizontal is more likely to be absorbed by surrounding buildings than light emitted directly upwards, although the former may lead to complaints of light trespass. The irrelevance of light emitted close to the horizontal for people in a town or city is recognized in one of the models of sky glow, which argues that light originating in towns and villages some distance from an observatory can be modelled as a large diffuse light source (Soardo et al., 2008).

Even if no light is emitted directly upwards, sky glow is still a possibility. This is because whenever light strikes a surface, some is reflected. Thus, for a lighting design based on illuminance, which, apart from traffic route lighting, is what is normally done, the higher are the reflectances of the illuminated surfaces, the larger will be the amount of light reflected and much of this reflected light would be directed up into the sky. In a sense, this widespread distribution of light is the price we pay for having photons available wherever we choose to place our eyes. Diffusely reflected light will not cause glare and is very unlikely to cause light trespass, but it does contribute to sky glow.

15.3.2 Light Trespass

Trespass is defined as an encroachment or intrusion. Most buildings have windows or roof lights, and it is these that provide the route for light trespass to occur indoors. Whether or not light entering a property after dark is considered a trespass is a matter of individual perception. Most people expect some light to enter after dark and it is only when the amount of light entering is considerably above that expected or the amount of light entering varies frequently that complaints are likely to arise. Thus, complaints of light trespass are influenced by both the consequences of the light trespass and the individual's psychology. Light that interferes with sleep is more likely to be the subject of complaint than light that has no such effect. Light from a neighbour's security light is more likely to be the subject of complaint than light from the complainant's own security lighting.

15.3.3 Glare

Glare is both a physiological and psychological phenomena. Physiologically, glare is caused by light scattered in the eye and by the range of luminances present in the visual field (see Section 5.4.2). Psychologically, it is related to the experience of reduced visibility as well as more general discomfort and irritation. Light sources that reduce visibility through light scatter can be irritating as well as uncomfortable. Even when the consequences of light scatter are negligible, the scatter may be noticeable and hence annoying. Similarly, discomfort can be caused by having an excessive range of luminances present in the visual scene, even when the high-luminance objects in the visual scene have very little impact on the observer's visual capabilities. This being a psychological phenomenon, it is also possible for the level of discomfort and annoyance to be enhanced by factors having nothing to do with the luminous environment, for example, by the fact that the glare source is owned by a disliked neighbour.

15.4 CONSEQUENCES OF LIGHT POLLUTION

The most obvious consequence of sky glow is the reduction in visibility of stars and other astronomical features. This reduction occurs because light scattered either in the atmosphere or in the eye has the effect of superimposing a luminous veil over the scene. The effect of this luminous veil is to reduce the luminance contrasts of the elements of the scene which means an inevitable reduction in visibility. Many stars are small and have luminance contrasts close to threshold which is why sky glow can dramatically reduce the ability to see features of the night sky such as the Milky Way.

While a reduction in visibility of the night sky is the most obvious consequence of sky glow, light pollution can have effects on human health. Humans are diurnal animals that have evolved under bright light during the day and little light at night. This pattern of bright light by day and little light at night is one of the most potent cues used to entrain the circadian timing system (see Section 3.3). Frequent disruption of the circadian timing system is believed to be bad for human health. Certainly, doing many years of rapidly rotating night shifts, which are associated with circadian disruption, is known to lead to poor health (Schernhammer and Thompson, 2011). Unfortunately, exactly how much light at night is sufficient to cause circadian disruption is not known although a threshold of 30 lx at the eye for 30 min has been suggested based on suppression of the hormone melatonin (Figueiro et al., 2006). If this is correct, then it suggests that outdoor lighting, as normally experienced, is marginal for adversely affecting human health (Rea et al., 2012b).

A much clearer case of light pollution affecting human health is when light trespass interferes with sleep. Broken or truncated sleep leads to a sleep deficit with the resulting feelings of tiredness, confusion and irritability. Broken or truncated sleep can occur when light at night enters a bedroom window, particularly if the amount of light varies suddenly. This may happen when a pattern of shadows cast by a tree illuminated by a street light moves as the wind blows or when a security light is triggered intermittently.

Humans are not the only creatures affected by light pollution (Rich and Longcore, 2006). The growth of many plants is influenced by the day length and by the amount of energy available in the radiation incident on the plant. Light pollution can alter the apparent day length and provide additional energy leading to excessive growth and flowering at inappropriate times of the year. As for fauna, many creatures, such as owls and bats, are active at night and sleep during the day. For these creatures, light pollution can cause confusion about day length and thereby limit their opportunities for feeding. Other creatures are attracted to light at night (Bruce-White and Shardlow, 2011). Moths are the obvious example but there are also cases of passerine birds colliding with tall floodlit buildings, resulting in mass deaths (Gauthreaux and Belser, 2006). As a result, some building owners have agreed to turn off their floodlighting during the birds' migration period. Yet, other creatures, such as turtles, can be confused by light at night and so find their way to the nearest road rather than the sea. It is important to remember that for every creature afflicted by light at night, there are likely to be others that benefit. For example, a light source that attracts insects and moths at night is likely to have some well-fed toads squatting underneath it.

15.5 REACTIONS TO LIGHT POLLUTION

Given that all outdoor lighting and some indoor lighting leaking through windows will inevitably make a contribution to light pollution, it is now necessary to consider how people react to this pollution. The answer is in many different ways, ranging from complaints by individuals, through activities by advocacy groups, to legislation by governments.

Sky glow has become the focus of a number of advocacy groups (Mizon, 2002), the most influential of which has been the International Dark-Sky Association. Like all advocacy groups, their activities range from raising awareness of sky glow as a problem to suggesting solutions for individuals and communities (IDA, 2012). Awareness is raised by circulating satellite images showing the amount of light leaving the Earth (Figure 15.4) as well as occasionally overexposed images of poor lighting installations. One of the most successful initiatives of these advocates has been the introduction of dark-sky parks and reserves. These are locations where the use

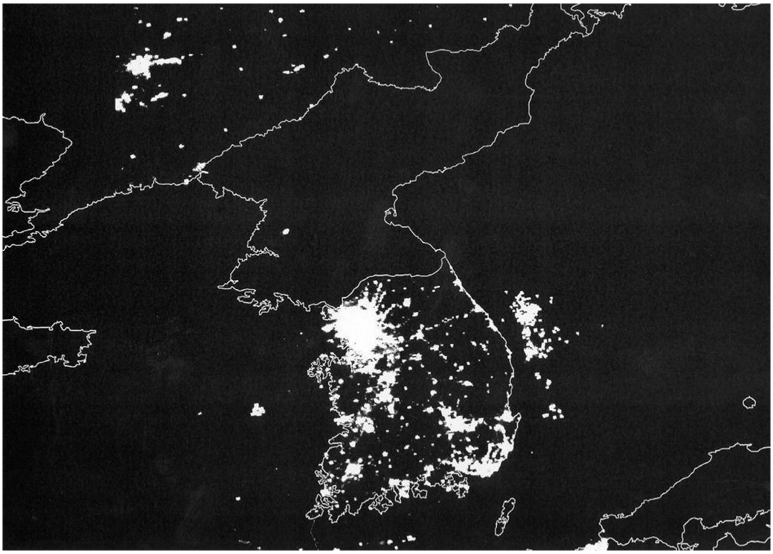


FIGURE 15.4 A satellite image of light leaving Earth over the Korean peninsula.

of light outside at night is allowed but only after great care is taken to minimize sky glow. This is done to ensure that astronomers, both professional and amateur, can see the night sky. In the United Kingdom, there is a dark-sky park in the 300-square-mile Galloway Forest in Scotland and a dark-sky reserve in the Exmoor National Park in England. In addition, the island of Sark in the Channel Islands has been declared a dark-sky island. While large parts of these locations are characterized by few people and even fewer paved roads, there are still villages with schools and businesses that may require exterior lighting for safety or production. However, it is worth noting that restrictions on sky glow can have a financial value. Tourism based on the ability to see the night sky is being actively promoted in these areas.

Of course, many places have too high a population to be suitable for a dark-sky reserve, but there is still something that can be done through the planning system. In the United States, the IESNA and the International Dark-Sky Association have worked together to produce a model lighting ordinance (IESNA and IDA, 2011c). Planning in the United States is largely a function of cities, towns and counties. The model lighting ordinance provides a framework for any such authorities that want to set up legal limits on the amount and type of lighting that can be used outdoors to do so.

In the United Kingdom, the government has recognized light as an aspect of environmental health, like noise, and has identified it as a potential statutory nuisance in the Clean Neighbourhoods and Environment Act, 2005. This status allows any individual troubled by lighting to complain to the authorities who then have the legal backing to demand remedial action be taken if they consider the complaint to be justified. Of course, some facilities are exempt. Exemptions include roads, airports, port facilities, military facilities, railway premises, tramway premises, bus stations, public service vehicle operating centres, goods vehicle operating centres, lighthouses and prisons. A report for the Department for Environment, Food and Rural Affairs contains a proposed methodology for examining complaints about light trespass from security and decorative lighting and summarizes the effects of various remedial actions that might be taken (Temple/NEP Lighting Consultancy, 2006).

While much of this activity is in many ways commendable, it is important to recognize that legislation or regulations driven by an advocacy group are likely to be biased in favour of that group. This can generate resistance because what constitutes the astronomer's pollution is often the business owner's commercial necessity and sometimes the citizen's preference. Residents of cities and towns like their streets to be lit at night for the feeling of safety the lighting provides. Similarly, many roads are lit at night to enhance the safety of travel. Businesses use light to identify themselves at night and to attract customers. Further, the floodlighting of buildings and the lighting of landscapes are methods used to create an attractive environment at night (Figure 15.5). The problem of light pollution is how to strike the right balance between these conflicting desires.

Different societies solve this problem in different ways but something that is always useful is a quantitative understanding of the magnitude of the problem. Vos and van Bergem-Jansen (1995) determined this for a specific activity, the lighting of greenhouses at night to promote plant growth. Such lighting is widely used in the Netherlands from September to mid-May, and the greenhouses are commonly situated in the vicinity of residential areas. The illuminances on the plants are typically in the range 3000–4000 lx and are provided by high-pressure sodium lamps. To determine community reaction, a survey was carried out in 10 areas around such lighted greenhouses, responses being obtained from 391 residents. Light trespass was assessed by measuring the illuminance on the house facade and by asking if the resident was annoyed by light from the greenhouses. The illuminance on the facades of the houses varied from 0.003 to 2 lx, all of which are below the allowed maximum

FIGURE 15.5 Façade lighting being used to enhance the dramatic impact of Dover Castle. (Courtesy of LPA Lighting and Photography, Leeds, UK.)

recommended by the Institution of Lighting Professionals (ILP, 2011) apart from dark-sky reserves (see Table 15.2). The percentage of respondents who were at least 'a little annoyed' by the illumination of their rooms or garden by light from the greenhouses was about 7%, while only about 3% were 'highly annoyed'. There was no simple relationship between the level of annoyance and the illuminance on the facade.

As for sky glow, this was quantified by the luminance of the sky measured at an angle of 15° above the line of sight to the greenhouse. This luminance ranged from 0.09 to 0.67 cd/m^2. The percentage of respondents who were at least 'a little annoyed' by the increased sky glow ranged from 15% to 45%. The percentage of respondents who were 'very annoyed' by the increased sky glow ranged from 0% to 18%. The percentage annoyed in both categories increased with increasing luminance, although a closer relation between the level of annoyance and luminance was obtained by using the ratio of the luminance of the sky above the greenhouse to the luminance of a dark part of the sky not illuminated by the greenhouse, another illustration of the importance of contrast to visual perception (Figure 15.6). Of course, these data are for one situation in one country but they do indicate what can be done to determine whether complaints about light pollution are common in a community or are the opinions of a few assertive individuals.

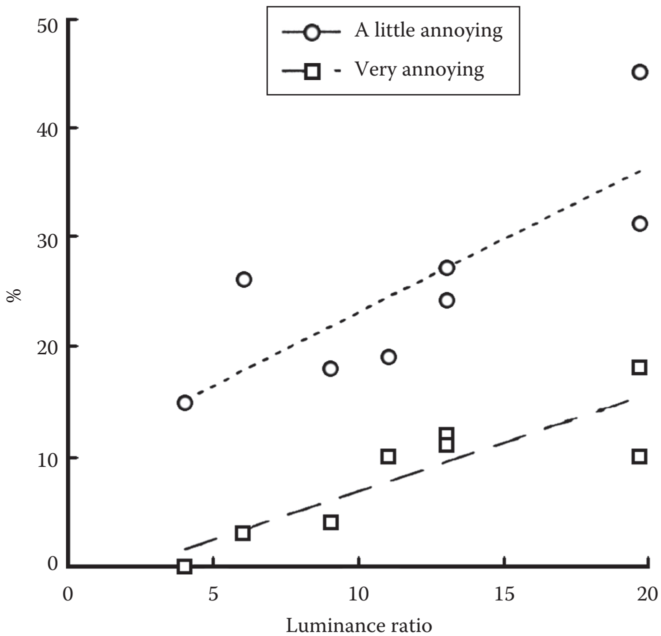


FIGURE 15.6 Percentage of survey respondents who rated the sky glow above greenhouses illuminated at night at least as 'a little annoying' or at least as 'very annoying' plotted against the ratio of the luminance of the sky at an angle of 15° above the greenhouses and the luminance of a dark part of the sky not illuminated by the greenhouses. (After Vos, J.J. and van Bergen-Jansen, P.M., *Lighting Res. Technol.*, 27, 45, 1995.)

Another set of data that gives an insight into the level of concern about light pollution in England is contained in a report on the number of statutory nuisance complaints to local authorities since the introduction of the Clean Neighbourhoods and Environments Act (DEFRA, 2010). In the 3 years since the act was implemented, 4309 complaints about lighting had been made to the 114 local authorities that responded to a survey, suggesting an average complaint rate of 12 complaints per authority per year. Of these, about two-thirds were concerned with domestic security lighting. A common feature of these complaints was the earlier disagreements between neighbours, the implication being that lighting was seen as just another weapon in the battle. As for non-domestic lighting, commercial and industrial security lighting was the most common cause of complaint. All the complaints, both domestic and non-domestic, related to light trespass, the consequences commonly being sleep deprivation or headaches as well as interference with normal living activities. Of these 4309 complaints, less than 1% had resulted in a formal abatement notice being issued which suggests that many of the complaints either were unjustified or were dealt with by discussion between the parties without recourse to legal measures.

What these two studies suggest is that the populace are not as seriously exercised about light pollution as the advocates claim. This view is supported by the fact that a Europe-wide survey of attitudes to the environment conducted by the European Commission failed to list light pollution among the 15 possible sources of concern (EC, 2008). However, even if more surveys were done and the results also showed a lack of widespread concern with light pollution, this would still not offer a justification for ignoring the problem. This is because, in an example of serendipity, the actions required to limit light pollution have other beneficial consequences. Light emitted directly into the sky is a waste, unless it is inevitable as is the case for floodlighting from the ground and for some forms of landscape lighting. Likewise, lighting that causes light trespass or glare can be said to be a source of visual discomfort. Therefore, designing lighting to limit light pollution can be said to lead to more efficient and better-quality lighting.

15.6 LIMITING LIGHT POLLUTION

There are a number of methods for limiting light pollution ranging from need through technology to design. Each will be discussed in turn.

15.6.1 Need

The first and most effective means to limit light pollution is not to have any light. This means carefully considering if outdoor lighting is necessary at all. Outdoor lighting is usually provided for one or more of a number of reasons. Among the more common are the following: to enhance safety of movement, for example, on roads and paths; to provide information, for example, road signs; to enable work to be done, for example, in a container terminal; to provide security by making surveillance of a space possible, for example, in a car park; to lengthen the time for which outdoor facilities can be used, for example, on a tennis court; to advertise products for sale, for example, a car dealer's forecourt; and to increase the attractiveness of an area, for example, by floodlighting historic buildings.

When considering the need for outdoor lighting, the rationale for the proposed lighting has to be assessed. This rationale should consider what the expected benefits are, what lighting criteria are to be met, and over what area and over what time period the lighting should be provided. There is little benefit in lighting the whole of a supermarket car park in the middle of the night when there are few customers and those who are there will park close to the doors. An assessment of the need for outdoor lighting of new commercial, retail, sports and large residential facilities will usually occur when planning permission is being sought. The SLL publishes a document that provides a structure to assist with such an assessment (SLL, 2011).

15.6.2 Technology

The light source and luminaire chosen to deliver lighting can make a dramatic difference to the amount of light pollution produced. One of the earliest attempts to reduce sky glow involved the use of the low-pressure sodium light source for road lighting in cities adjacent to observatories. This approach was initially effective because astronomers could easily filter out the monochromatic spectrum of the low-pressure sodium light source, but, today, it has largely been abandoned, for two reasons. The first is that the nonexistent colour rendering properties of the low-pressure sodium light source make it an unattractive prospect for towns and cities. The second is that the growth in the use of light outdoors by commercial and residential property owners, using a wide range of light sources, has simultaneously increased the amount of light being emitted and undermined the effectiveness of the use of low-pressure sodium light sources by local authorities.

But there are still three reasons to consider light spectrum when selecting a light source for outdoor lighting. These are the wavelength-dependent nature of light scatter in the atmosphere, mesopic vision and brightness perception. Rayleigh scattering by air molecules ensures that short-wavelength light will be scattered more than long-wavelength light. This suggests that light sources with a spectrum rich in the short-wavelength end of the visible spectrum should be avoided. Bierman (2012) has provided an estimate of the magnitude of the difference in scattering for two light sources: a 2050 K high-pressure sodium source and a 6500 K phosphor-converted light-emitting diode (LED), the former being the light source most widely used for road lighting in the United States and the latter its proposed replacement. For an atmosphere containing only air molecules and no aerosols, the LED source will produce 22% more scatter than the high-pressure sodium source. However, such an atmosphere is unreasonable. The atmosphere over inhabited areas, which is where outdoor lighting is used, always includes aerosols, and Mie scattering from aerosols is not wavelength dependent in the visible region. Therefore, adding in aerosols reduces the percentage difference in scatter between the two light sources to a range of about 10%–20%.

Mesopic vision lies between photopic vision where the cone photoreceptors are dominant and scotopic vision where only the rod photoreceptors are active (see Section 2.3.2). Much outdoor lighting produces luminances that lie in the mesopic range. Why this matters is that all the photometric quantities used in lighting design assume photopic vision, but in the mesopic state, the spectral sensitivity of the retina, apart from the fovea, is shifted towards the short-wavelength end of the visible range.

This means that choosing a light source with more energy at the short-wavelength end of the visible range, that is, a bluer light, can provide similar off-axis visual capabilities at a lower luminance although at the lower luminance the performance of the fovea will be degraded. Whether or not this is acceptable is up to the designer.

As for the effects of light spectrum on brightness perception, this arises because the photometric quantity luminance, which is a correlate of brightness, is based on the operation of the achromatic channel of the visual system but the perception of brightness is based on the operation of both the achromatic and the chromatic channels (see Section 6.2.2.4). This means that a light source that provides greater stimulation to the colour channels can produce a perception of greater brightness at the same luminance or an equal perception of brightness at a lower luminance.

Taken together, these three effects mean that the choice of a light source for limiting sky glow is always going to be a compromise. Light sources with a lot of power at the short-wavelength end of the visible spectrum will produce more scattered light and hence more sky glow unless the spectrum is such that a lower luminance can be used without detrimental effects on visual capabilities and brightness perception.

Having chosen a light source, the next step is to select a luminaire. For many years, the simplest advice on how to limit sky glow was to use what was then called a full cut-off luminaire (IESNA, 2000a). A full cut-off luminaire is defined as having zero luminous intensity at or above 90° from the downward vertical and no luminous intensity in the range 80°–90° from the downward vertical greater than 10% of the light source luminous flux. Anxious to avoid such complexities, people concerned about light pollution often use an alternative term, fully shielded, to describe luminaires that emit no light directly above the horizontal plane through the luminaire. Fully shielded outdoor luminaires typically have the aperture through which light is emitted sealed by a transparent, flat lens. Luminaires where the lens drops below the plane of the aperture are not fully shielded.

Unhappy with such simplification and aware of criticisms of their luminaire classification system (Bullough, 2002b), the IESNA has developed a new outdoor luminaire classification system based on the percentage of light source luminous flux emitted in a number of zones about the luminaire (IESNA, 2007b). Figure 15.7 shows a sphere centred on the luminaire, divided into three zones. The luminous flux emitted into the hemisphere above the luminaire is the uplight. The luminous flux emitted intothe quarter of the sphere in front of the luminaire and below the horizontal plane is the forward light and that emitted into the quarter of the sphere behind the luminaire and below the horizontal plane is the backlight. The remaining zone not evident in Figure 15.7 is the trapped light, which is the luminous flux emitted by the light source that does not get out of the luminaire. Uplight, forward light, backlight and trapped light are all expressed as percentages of the light source luminous flux. The solid angles subtended by the uplight, forward light and backlight zones are all subdivided according to the angle from the downward vertical from the luminaire: uplight into two classes and forward light and backlight each into four classes. Maximum absolute luminous flux values have been set for both the subdivisions in the uplight zone, for all four of the subdivisions of the backlight zone and for the uppermost part of the forward light zone (IESNA, 2011a). These limits are varied so as to divide luminaires into six classes for backlight, uplight and glare, the whole

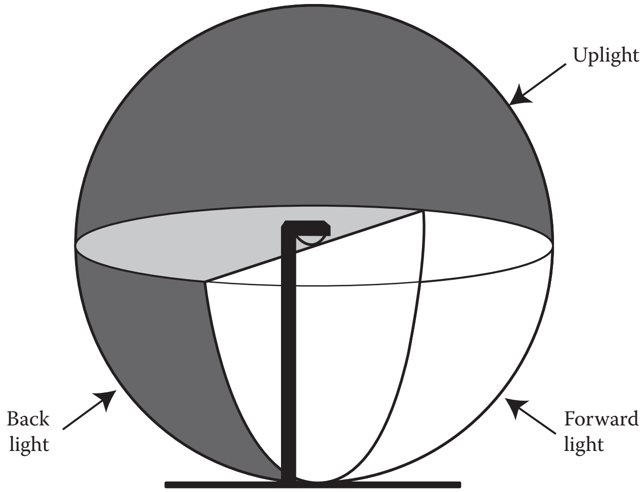


FIGURE 15.7 Three zones around a luminaire according to the IESNA outdoor luminaire classification system. (From Illuminating Engineering Society of North America (IESNA), *Luminaire Classification System for Outdoor Luminaires*, Technical Memorandum TM-15-07, IESNA, New York, 2007b.).

pattern being summarized as a BUG rating. For those concerned with sky glow, the most restricted uplight class is advised. For those concerned with light trespass, the most restricted backlight class is suggested. For those concerned with glare, the most restricted class of glare rating is recommended.

Unfortunately, while selecting luminaires based on this classification system will certainly be effective in reducing light trespass and limiting glare, it may be less effective in reducing sky glow, for two reasons. The first is that restricting the upward light output from luminaires only limits the amount of light directly contributing to sky glow but ignores the indirect contribution of light scattered on the path to the surface to be illuminated as well as the light reflected upwards from the illuminated surfaces. These sources of scattered light can be major factors in sky glow. The second is simply that such advice considers the luminaire in isolation and not as part of a lighting system. Keith (2000) calculated the total number of lumens going up into the sky from a roadway lighting installation, per unit area of road illuminated, including both light directly emitted upwards and light reflected from the road and its surroundings. What he found was that if using luminaires with a more closely controlled luminous intensity distribution demanded a closer spacing to meet the road lighting luminance uniformity criteria, more light would go up into the sky.

15.6.3 Design

Even when the light source and luminaire are selected to minimize light pollution, the installation may still make a significant contribution to light pollution because of the amount of light delivered. Brons et al. (2008) collected designs for outdoor lighting installations covering 66 car parks, 33 roads and 20 sports facilities. The designs

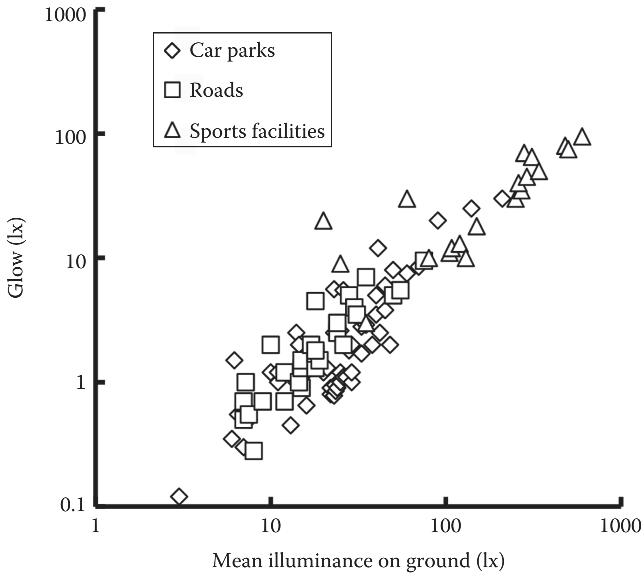


FIGURE 15.8 The area-weighted average illuminance leaving a site (Glow) plotted against the illuminance on the ground for the lighting of 66 car parks, 35 roads and 20 sports facilities. (After Brons, J.A. et al., *Lighting Res. Technol.*, 40, 201, 2008.)

are said to represent common practice and to follow the recommendations made by the CIE for sites in Europe and by the IESNA for sites in North America. Once a design had been completed, a virtual box was placed around the site on the property boundary with the ceiling set at 10 m above the height of the tallest luminaire. Then, the area of each face of the box and the mean illuminance on that face were calculated, including reflected light. These data were used to calculate the area-weighted average illuminance on the walls and ceiling of the box, a measure called Glow that quantifies the amount of light leaving the property. Figure 15.8 shows Glow plotted against the average illuminance on the floor of the box, that is, on the ground. One thing is clear from Figure 15.8. The greater is the amount of light used to illuminate the ground, the greater is the amount of light leaving the site and hence the greater is risk of light pollution occurring.

This demonstrates that determining how much light should be used on a site is an essential prerequisite for controlling light pollution. How much light is required depends on the purpose of the lighting. There are widely used recommendations for road lighting, for work outdoors, for sports and for security lighting (BSI, 2003, 2007a; SLL, 2006b, 2012b; IESNA, 2011a). These recommendations are applicable regardless of location because they are based on what is required to do the tasks associated with the location. However, for the purposes of advertising and increasing attractiveness, it is reasonable to take the location of the lighting into account. This is because what is required to stand out in a city centre is very different from what is needed in a rural area. The CIE has published recommendations that address this problem by defining four environmental zones (Table 15.1) (CIE, 2003). The information used to identify an environmental zone is qualitative rather than quantitative,

TABLE 15.1
Zoning System of the CIE

Zone	Zone Description and Examples of Subzones
E1	Areas with intrinsically dark landscapes: national parks and areas of outstanding natural beauty (where roads are usually unlit)
E2	Areas of 'low district brightness': outer urban and rural residential areas (where roads are lit to residential road standard)
E3	Areas of 'middle district brightness': generally urban residential areas (where roads are lit to traffic route standard)
E4	Areas of 'high district brightness': generally urban areas having mixed recreational and commercial land use with high night-time activity

Source: Commission Internationale de l'Eclairage (CIE), *Guide on the Limitation of the Effects of Light Trespass from Outdoor Lighting Installations*, CIE Publication 150, CIE, Vienna, Austria, 2003.

a matter of common sense rather than unthinking numbers, but some guidance can be given in terms of the standard of road lighting used and population density. As a general rule, zone E1 has no road lighting and a low population density; zone E2 has road lighting lit to the standards of residential roads and a moderate population density; zone E3 contains roads lit to traffic route standards and a high population density. Zone E4 refers to areas of high activity after dark, such as out-of-town shopping centres and urban areas with a high concentration of restaurants and clubs. Here, road lighting is an uncertain guide as is population density. The only sensible guidance is the presence of large numbers of people after dark. It is important to appreciate that an environmental zone does not have to coincide with an administrative boundary such as a city, town or village. Each of these locales can be subdivided into a number of environmental zones depending on the activities expected in each area. Environmental zones can be used in local authority planning policies and therefore have an influence on what type and amount of lighting is permitted. It should also be noted that in addition to the CIE classification of environmental zones, there is one other class (E0): the dark-sky preserve, reserve or park recognized by the International Dark-Sky Association.

The ILP uses all these environmental zones in its recommendations (ILP, 2011). Table 15.2 gives the ILP recommendations that are applicable to area lighting provided by luminaires mounted on columns or on buildings. The upward light ratio is the percentage of luminous flux from the whole lighting installation that is emitted above a horizontal plane through the luminaires. Essentially, this criterion attempts to reduce sky glow by limiting the proportion of light emitted directly upwards. In practice, meeting this criterion requires careful selection of luminaires and attention to how these luminaires are mounted and aimed. It is important to note that limiting the upward light ratio does nothing to limit the absolute contribution of the installation to sky glow. That will depend on the illuminance delivered to the ground (see Figure 15.8). For the same illuminance on the ground, an installation that does

TABLE 15.2
Lighting Recommendations for Avoiding Obtrusive Light for Area Lighting

Environmental Zone	Maximum Upward Light Ratio (%)	Maximum Illuminance on Windows (lx)	Maximum Luminaire Luminous Intensity (cd)
E0	0.0	0	0
E1	0.0	2	2,500
E2	2.5	5	7,500
E3	5.0	10	10,000
E4	15.0	25	25,000

Source: Institution of Lighting Professionals (ILP), *Guidance Notes for the Reduction of Obtrusive Light*, ILP, Rugby, U.K., 2011.

not exceed the maximum upward light ratio will make a smaller contribution to sky glow than one that does exceed the maximum upward light ratio, but if the former provides a higher illuminance, it may make a greater contribution to sky glow than the latter.

The maximum illuminance on the centre of windows is designed to limit light trespass into buildings. Meeting this criterion again calls for careful selection and aiming of luminaires. If this is not enough, then the use of some form of baffle may be necessary. It is important to note that this criterion is cumulative in that it takes into account all the light striking the window, not just the light from a new installation. Different planning authorities may approach this limit in different ways. One may decide that because existing lighting installations already provide an illuminance on a window that is close to the maximum allowed, no exterior lighting will be permitted on a new development. This will undoubtedly be effective in limiting light trespass but may inhibit development in the area. Another planning authority may decide that exterior lighting on a new development is required but may set a much lower illuminance limit to ensure that the total does not exceed the recommended maximum. Yet, another may decide to require the owners of existing lighting installations to reduce their contribution to light trespass so as to allow new development to occur. It is also possible that the planning authority may ignore the cumulative effect altogether and simply apply the maximum illuminance at the window to each installation separately. It could also be argued that all this bureaucratic manipulation is unnecessary. If an individual householder is bothered by light trespass, it is only necessary to fit heavier curtains, blinds or shutters to the window to solve the problem.

The maximum luminous intensity of the luminaire represents an attempt to control glare. It should only be applied to viewing directions that are likely to cause discomfort or disability glare. Again, meeting this criterion will depend on the choice and aiming of the luminaires.

Although each criterion has been discussed separately, it should be understood that for any given installation, all that are relevant should be met. For example, when lighting a car park, the upward light ratio, the maximum illuminance on the windows of nearby buildings and the maximum luminous intensity in relevant directions are all important if sky glow, light trespass and glare are to be limited. Other authoritative bodies have published similar but not identical recommendations (IESNA, 2000b; CIE, 2003; SLL, 2012c).

The existence of environmental zones and the associated lighting criteria are not sufficient to ensure that they will be used by designers. What is also required is a simple method to predict the contribution a lighting installation will make to sky glow as well as the likelihood of light trespass and glare, at the design stage. Commercial software is available for calculating the illuminances falling on defined surfaces, both real and virtual, for many forms of outdoor lighting including area lighting, floodlighting and security lighting. At the moment, none of this software deliberately sets out to quantify the contribution the lighting makes to sky glow or the extent to which it will cause light trespass or glare although some is flexible enough to be used for these purposes if desired. However, a comprehensive approach to quantifying obtrusive light using existing software has been developed (Brons et al., 2008). This approach, called the outdoor site-lighting performance (OSP) method, uses a virtual, transparent shoebox surrounding a property. The virtual shoebox has vertical sides at the property boundary and a flat ceiling 10 m above the highest mounted luminaire in the installation or the highest point of the property illuminated. Conventional software can be used to calculate the illuminance falling on the shoebox surfaces. By identifying the location and magnitude of the maximum illuminances on the vertical surfaces of the shoebox, the potential for light trespass can be established. The illuminances on the vertical surfaces represent a worst case for light trespass, that is, where there is a window actually at the boundary. At many sites, the nearest window may be some distance from the site boundary so the illuminance there will be a lot less. Nonetheless, ensuring that the maximum illuminance at the vertical surfaces of the shoebox meets the recommendations made to avoid light trespass in Table 15.2 can save a lot of aggravation and expense after the lighting has been installed. Predicting the illuminances at the boundary of the site simply indicates where a light trespass problem is likely to occur, not what the solution might be. Possible solutions include choosing a luminaire with a more appropriate luminous intensity distribution, moving the luminaire further into the site and away from the property boundary, planting screening vegetation and fitting some form of baffle to the luminaire.

The OSP shoebox approach is consistent with the way people think about property rights. Owning property confers considerable freedom of action on the owner within the property boundaries, provided those actions do not impinge negatively on others nearby or on the public good. The OSP shoebox approach is both flexible and realistic. It is flexible in that different maximum illuminance limits can be set by different communities, using the environmental zones if desired. It is realistic in that it uses widely available software to make the necessary calculations; decisions on actions necessary to avoid light trespass can be made at the design stage; it does not require detailed knowledge of what surrounds the property being lit, knowledge that is often not available to the designer; and it includes the contributions of both direct and reflected light.

The OSP shoebox approach can also be used to estimate the contribution of the lighting installation to sky glow. This is done by calculating the average illuminance on the vertical and top planes of the shoebox. Brons et al. (2008) have provisionally recommended maximum values of this metric of 30 lx for zone E4, 10 lx for zone E3, 3 lx for zone E2 and 1 lx for zone E1.

So far so good, but what about glare? It is always possible to assess disability glare using the threshold increment measure developed for road lighting (see Section 10.4.2), but this still leaves open the question of discomfort glare. Bullough et al. (2008) conducted 10 investigative experiments on people's experience of discomfort under outdoor lighting conditions when looking directly at the light source. From these experiments, a method was developed for predicting the level of discomfort based on three illuminances measured at the observer's eye (see Section 11.6). Figure 11.15 shows the relationships between the predictions of this model and the mean de Boer ratings given for all of the experiments conducted. The variance in the de Boer ratings explained by the model was 59%. Given the large individual differences found in most studies of discomfort glare (see Section 5.4.2.2), this percentage explained is quite reasonable. No doubt, it could be improved by manipulating the other factors that are known to influence discomfort glare but were not considered such as light spectrum and surround luminance (Sweater-Hickcox et al., 2013). Although not perfect, this illuminance method does have the great virtue of being relatively simple to implement at the design stage. Once an observer's position and the luminaire of interest have been selected, currently available software can be used to calculate all three illuminances, and hence the predicted discomfort glare score can be calculated and that can, in turn, be converted to a de Boer rating. A de Boer rating of four or less is conventionally considered unacceptable.

The implication of these developments is that the potential for a given lighting installation to add to sky glow and cause light trespass and glare can readily be identified using available design software by calculating the illuminances received at the property boundaries and at the observer's eye. This should enable the extent to which any proposed lighting installation will cause light pollution to be predicted and the design modified if necessary.

15.6.4 Timing

Another option in dealing with light pollution is to pay careful attention to the timing of the use of light. Unlike most other forms of pollution, when the light source is extinguished, the light pollution goes away very rapidly. This suggests that a curfew defining the times when lighting can and cannot be used can have a dramatic effect. Of particular value would be the application of a curfew to the use of light for commercial purposes, other than for security. This is because one of the major forces leading to obtrusive lighting is the commercial need to be noticed. There is little point in using light at night to attract attention when there is no one about to notice. This may be why the French government has proposed that lighting inside and outside shops, offices and public buildings should be turned off from 01.00 to 07.00 h. It will be interesting to see if this proposal is implemented and, if it is, how well it is enforced.

TABLE 15.3
Lighting Recommendations for Avoiding Obtrusive Light for Area Lighting during Times of Curfew

Environmental Zone	Maximum Illuminance on Windows (lx)	Maximum Luminaire Luminous Intensity (cd)
E0	0	0
E1	0[a]	0
E2	1	500
E3	2	1000
E4	5	2500

Source: Institution of Lighting Professionals (ILP), *Guidance Notes for the Reduction of Obtrusive Light*, ILP, Rugby, U.K., 2011.

[a] 1 lx is allowed for road lighting.

A less draconian approach is recommended by the ILP (2011). Their recommendations for maximum illuminance on windows and maximum luminaire luminous intensity criteria for area lighting given in Table 15.2 are relevant when there is no curfew in operation. When there is a curfew, the values of these criteria in Table 15.2 should be applied before the curfew takes effect and those given in Table 15.3 should be applied after the curfew takes effect. Meeting these criteria will reduce light trespass and glare during curfew times but to do that implies there will have to be a reduced light output from the installation and consequently reduced sky glow. Of course, the criteria in Table 15.3 imply that during curfew times, the installation is producing some light, but is this necessary? There are many examples of decorative lighting such as floodlighting and landscape lighting that have no function in the middle of the night. A similar argument can be made for many sports lighting installations after the game has finished and the spectators have left. Such installations should be switched off during the curfew.

15.7 THE FUTURE

Light pollution is unlikely to disappear as a concern any time soon. This is because there are global trends operating both for and against light pollution. One trend pointing towards increased light pollution is the growth in population of many countries, more people usually means more light being used. Another is the economic development of populous countries such as China and India. A glance at Figure 15.4 should be enough to demonstrate the role of economic development in the use of light. South Korea is easily distinguished from North Korea. Finally, technology is always capable of producing new sources of light pollution. For example, the development of LED video billboards is causing new problems with light trespass. These billboards have average luminances as high as 7000 cd/m^2 when showing a white image because they need to look bright during the day, but, all too often, the luminance is not sufficiently reduced after dark, despite advice to do so (Lewin, 2008). Further, these billboards change the displayed image frequently meaning the average luminance changes frequently. This means anyone with a window close to one of these billboards will experience frequently varying amounts of light trespass, the variability making the trespass particularly disturbing.

Against these trends are arrayed legislation and technology. Increasingly, national and local authorities in developed countries are constructing a legal framework that seeks to limit the amount and type of lighting used outdoors at night. The lighting industry has also recognized the potential market for products that minimize sky glow. As a result, there are now available many fully shielded luminaires suitable for use outdoors, so there is no excuse that suitable luminaires cannot be found. The latest developments in lighting controls are also of interest. Combinations of sensors, dimming controls and LED light sources have been put together to produce adaptive outdoor lighting systems. These are systems where the amount of light produced is reduced dramatically when sensors indicate there is no one present, only to increase when presence is detected.

How the conflict between these opposing trends plays out will vary from country to country. It is to be hoped that in most countries the careless and wasteful use of light represented by light pollution will be reduced. This is easy to do for light trespass and glare by the careful selection, positioning and aiming of luminaires. Unfortunately, it is not so easy for sky glow. Sky glow is an inevitable consequence of outdoor lighting. The more light that is emitted outdoors after dark, the more sky glow there will be. It is only by reducing the amount of light used outdoors at night and the hours for which it is used that sky glow will be reduced. This means paying attention to all forms of outdoor lighting as well as to light leakage from buildings through windows. It is easy to be concerned only with the worst cases of light pollution, but unless these are common, they make a small impact on overall sky glow. Attention also has to be given to the most widely used examples of outdoor lighting. Small reductions from large numbers of installations can have a large impact on sky glow. This is why the first questions that anyone concerned with purchasing or designing a new outdoor lighting installation should ask themselves is ‘Is this lighting necessary and, if it is, when is it necessary?’ Given that a new lighting installation is deemed necessary, some of the main objectives of the design should be to eliminate light trespass and glare and to minimize the contribution to sky glow. If these objectives can be met, then the benefits of outdoor lighting will be enhanced and the problem of light pollution reduced.

15.8 SUMMARY

Light pollution can take three forms. These are sky glow, light trespass and glare. Sky glow refers to the increase in the luminance of the sky at night. It can be seen above most towns and cities as a flattened dome of light. Unlike sky glow, light trespass is a local phenomenon that causes disturbance to individuals. The classic event that provokes a complaint of light trespass is when light from a nearby outdoor luminaire enters a window. Glare comes in two main forms, disability and discomfort glare. The former affects visual performance while the latter simply causes discomfort.

Sky glow is caused by light scattered by the air molecules and aerosols in the atmosphere. Light trespass occurs when an excessive amount of light enters a property and interferes with the occupants' enjoyment of that property. Glare is associated with the presence of a wide range of luminances in the visual field. This can have both physiological and psychological effects.

The most obvious consequence of sky glow is the reduction in visibility of stars. This reduction occurs because light scattered in the atmosphere has the effect of superimposing a luminous veil over the scene resulting in a lowering of the luminance contrasts in the scene. Many stars are small and have luminance contrasts close to threshold which is why sky glow can dramatically reduce the ability to see features of the night sky. Light trespass can affect human health when it interferes with sleep. Broken or truncated sleep leads to a sleep deficit with the resulting feelings of tiredness, confusion and irritability. Broken or truncated sleep can occur when light at night enters a bedroom window, particularly if the amount of light varies suddenly. Glare can reduce visibility and cause visual discomfort.

Humans are not the only creatures affected by light pollution. The growth of many plants is influenced by the day length and by the amount of energy available in the radiation incident on the plant. As for fauna, many creatures are active at night and sleep during the day. For these creatures, light pollution can cause confusion about day length and thereby limit their opportunities for feeding. Other creatures are attracted to light at night which may result in inappropriate behaviour.

People's attitudes to light pollution vary widely. The problem is that what constitutes the astronomer's pollution is often the business owner's commercial necessity and sometimes the citizen's preference. Residents of cities and towns like their streets to be lit at night for the feeling of safety the lighting provides. Similarly, many roads are lit at night to enhance the safety of travel. Businesses use light to identify themselves at night and to attract customers. Further, the floodlighting of buildings and the lighting of landscapes are methods used to create an attractive environment at night. The problem of light pollution is how to strike the right balance between these conflicting desires.

One solution has been to promote the creation of dark-sky parks in sparsely inhabited areas. Another has been to classify light as a statutory nuisance like noise. Yet, another has been to develop a model lighting ordinance for use by local authorities seeking to control light pollution in their area. Probably, the most common activity has been to publish information on how to limit the various forms of light pollution. Sometimes, this consists of simply advocating the use of specific technologies such as fully shielded luminaires in which no light is emitted above a horizontal plane through the luminaire. On other occasions, design advice is given in the form of a system for classifying urban, suburban and rural areas into five different environmental zones and then to assign maximum upward light ratios, maximum illuminances falling on windows and maximum luminaire luminous intensities to each zone. These lighting criteria, when combined with an illuminance-based calculation method using conventional design software, enable the designer to predict the contribution of any outdoor lighting installation to sky glow as well as to identify where light trespass and glare might occur.

Of course, such solutions only apply when the installation is being used. A somewhat neglected solution to light pollution is based on timing. Unlike most other forms of pollution, when the light source is extinguished, the light pollution disappears. This suggests that a curfew on the use of light could have a dramatic effect. Of particular value would be the application of a curfew to the use of light for commercial purposes, other than for security. This is because one of the major forces leading to light pollution is the commercial need to be noticed. There is little point in using light at night to attract attention when there is no one about to attract.

Finally, it is important to appreciate that light trespass and glare are not inevitable consequences of outdoor lighting. By careful selection, positioning and aiming of luminaires, both can be avoided. However, sky glow is an inevitable consequence of outdoor lighting. The more light that is emitted outdoors after dark, the more sky glow there will be. It is only by reducing the amount of light used outdoors at night and the hours for which it is used that sky glow will be reduced. This means paying attention to all forms of outdoor lighting as well as light leakage from buildings through windows. This is why the first questions that anyone concerned with purchasing or designing a new outdoor lighting installation should ask themselves is 'Is this lighting necessary and, if it is, when is it necessary?' Given that a new lighting installation is deemed necessary, some of the main objectives of the design should be to eliminate light trespass and glare and to minimize the contribution to sky glow. If these objectives can be met, then the benefits of outdoor lighting will be enhanced and the problem of light pollution reduced.

16 Lighting and Electricity Consumption

16.1 INTRODUCTION

Daylight is a highly desired form of lighting (see Section 7.3.1) but fails reliably every day. Consequently, the developed world relies upon artificial light for much of the time. With very rare exceptions, this lighting is powered by electricity. Electricity is a refined fuel that is expensive to generate and to distribute. The generation of electricity often involves the burning of fossil fuels which itself sends carbon dioxide into the atmosphere. The end result of the accumulation of carbon dioxide in the atmosphere is believed to be global warming and climate change. As a result of this belief, governments around the world are making efforts to introduce electricity generating systems that produce less carbon dioxide and to reduce the demand for electricity. Globally, lighting is estimated to consume about 19% of all the electricity generated (IEA, 2006). It is also believed to be one application where demand might be considerably reduced. This is because lighting installations have relatively short lives compared to buildings, are easy to access and there already exist energy-efficient technologies that are not widely used. Attempts have been made to reduce electricity consumption by lighting through regulation, recommendation and design. Each will be discussed in turn.

16.2 LEGAL STATUS

Lighting practice is strongly influenced by regulations and recommendations. Regulations form a legal framework for the use of light. Recommendations provide advice on how to achieve desired lighting conditions. Regulations are published by governments and associated authorities. Recommendations are published by learned societies, professional and industrial organizations and advocacy groups. Together, regulations and recommendations influence the lighting of almost all places from offices to theatres, from tunnels to sports stadia. Guidance on lighting requirements can be found under many different names, such as codes, guides, recommended practices, handbooks and best practices. Regardless of the name, the first thing to be aware of when considering whether to follow such guidance is the legal status of the document. In principle, regulations derived from laws have to be followed but recommendations do not. In practice, things are not quite that simple. This is because some recommendations have legal standing by reference. This situation occurs when the guidance is generated by a body with no legal authority, such as a learned society or professional organization, but whose recommendations become widely accepted as good practice. The power of such recommendations lies in the risk of litigation. Anyone who has ignored such recommendations is not able to base their defence on following best practice. Indeed, following such recommendations may be a necessary requirement for maintaining professional indemnity insurance. This is the situation for many widely used lighting recommendations, such as those of the SLL (2012a) and the IESNA (2011a). Somewhat more remote but still with some legal power, although no legal standing, are the documents published by professional bodies to give guidance for specific applications, such as the Lighting Guides of the SLL and the Recommended Practices of the IESNA.

Having determined the legal status of the guidance, the next step is to examine the precision of any recommendations. This can vary widely from specific illuminances measured at specific positions to simple statements of desirable actions, such as that care should be taken to avoid veiling reflections. There is no simple relationship between level of precision and legal status. There are regulations that have very precise lighting requirements and those that contain only a statement of intent. There are also guides and practices published by professional organizations that contain precise recommendations alongside vague exhortations. For documents with legal standing, the level of precision tends to be related to the consequences of lighting failing. The more serious are the consequences of failure, the more precise the recommendations in documents with legal standing tend to be. Thus, where poor lighting will place the safety or health of the public at risk, or will offend against a public policy, such as reducing electricity consumption, the recommendations tend to be quantified and measurable. Where the consequences of failure are slight or uncertain, statements of intent are usually considered sufficient.

16.3 TRENDS IN LIGHTING REGULATION

For many years, the basis of policy as regards lighting was the health and safety of the public. Thus, sufficient and suitable lighting was required to make the performance of tasks easy, to minimize accidents and to avoid damage to the visual system. However, over the last decade, another factor has become dominant in policy – the desire to reduce electricity consumption or, more accurately, to limit the increase in electricity consumption. This policy has been implemented in two different ways. One approach has placed specific limits on power densities for lighting. This has the advantage of regulating the end rather than the means. The other is to ban the use of energy-inefficient technology. This approach regulates the means but not the end.

Probably, the most demonstrably successful example of the use of power density limits can be found in the State of California, the ninth largest economy in the world. There, power density limits for interior lighting were first introduced in 1978 and have been revised regularly since (CEC, 2008). The beauty of this approach is that specifying the maximum allowed lighting power density does not restrict the designer unduly. Rather, the lighting designer is free to allocate the amount and distribution of light and to choose the light sources to be used as desired, provided the lighting power density for the installation does not exceed the maximum. The maximum lighting power density can be applied to a whole building or, where different spaces in a building have very different visual requirements, on a space-by-space basis. The use of lighting controls to eliminate waste is also encouraged by the use of an effective lighting power density, the adjustment being made when specific lighting controls are incorporated into the design.

The skill in setting the maximum lighting power densities is to make them stringent enough so that they encourage the development of more energy-efficient products and designs, yet not so stringent that they cannot be met with existing technology without producing inadequate lighting. As an example of this process, Figure 16.1 shows the distribution of the ratio of lighting power densities for four types of building built in California between 1994 and 1998, to the relevant maximum allowed lighting power densities. Ratios greater than unity do not comply with the standard, while ratios less than unity do. It is clear from Figure 16.1 that the majority of these new buildings did comply with the regulations and that by making those requirements more stringent, there was an opportunity to reduce the electricity consumption further. This tightening of the maximum allowed lighting power densities occurred in 2001. It is also evident that a few of these new buildings did not comply with the relevant regulations, a fact that suggests the need for stricter enforcement. Such legal requirements, provided they are backed by clear enforcement policies, can be very effective in reducing the use of electricity for lighting. Certainly, luminaire manufacturers in the United States have acknowledged the California regulations as the driving force behind the increased production and

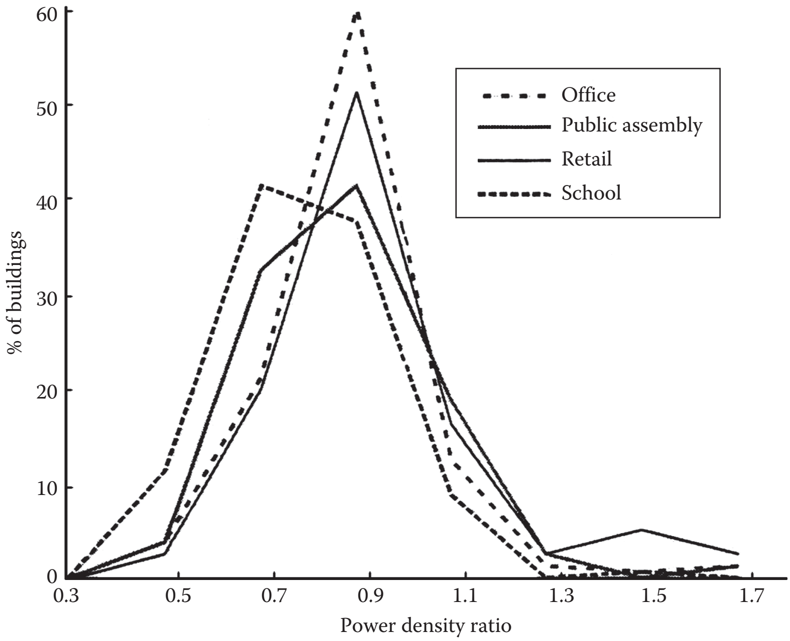


FIGURE 16.1 The distributions of the ratio of the actual lighting power density to the maximum allowed lighting power density permitted by regulation, in four types of buildings. Ratios greater than unity indicate non-compliance with the regulations. The distributions are based on a sample of 667 new buildings constructed in California between 1994 and 1998. (After RLW Analytics, *Non-residential New Construction Baseline Study*, Sonoma, CA, 1999.)

marketing of energy-efficient lighting technologies. Today, California is not alone in setting power density limits. Many other states have adopted the American National Standard 90.1 as the basis for their energy codes (ASHRAE, 2007). This standard includes power density limits for indoor and outdoor lighting and minimum criteria for lighting controls.

The other regulatory approach adopted for reducing electricity consumption by lighting is to ban the use of energy-inefficient equipment. An example of this can be found in Part L of the UK building regulations. These require that three out of four permanently installed luminaires, that is, not connected through a plug and socket, in the main spaces of new dwellings should be of the low-energy type. Low-energy luminaires are defined as using a light source with a luminous efficacy of more than 45 lm/W and having a light output of more than 400 lamp lumens. For offices, industrial and storage facilities, the average initial luminous efficacy should be not less than 55 luminaire lumens per circuit watt, while display lighting should have an average initial luminous efficacy of not less than 22 lamp lumens per circuit watt. This approach has also been extensively used in the United States. The Energy Policy Acts of 1992 and 2005 and the Energy Independence and Security Act of 2007 mandated energy efficiency standards for light sources, effectively banning a number of products.

Such market manipulation has been a regulatory tool for many years but only recently has this become evident to the general public. This is because it has now been applied the light source used by almost everybody at home, the incandescent lamp. For many years, electric lighting was unique among technologies in that the first electric light source invented, the incandescent lamp, remained the most popular because it was the light source of choice for homes. The popularity of the incandescent lamp to the householder is easy to explain. The first cost of the incandescent lamp is very low, it can be used in very simple luminaires without any control gear, it is easily dimmed, it produces full light output immediately, and although its colour properties are not ideal, people were used to them. True, the incandescent lamp has a low luminous efficacy and a short life (see Table 1.4) but this is more than overcome by its low first cost. Indeed, the fact that they have a short life means they have to be replaced frequently, a fact that makes the possible changeover from the incandescent lamp to a more energy-efficient light source relatively rapid. At first, the proposed substitute for incandescent lamp in the home was the compact fluorescent although now the light-emitting diode (LED) is also an option.

For more than 20 years, the lighting industry and government agencies tried to convince householders that a compact fluorescent is a more economic proposition than the incandescent, which it is if the lifetime costs are considered. These attempts took various forms at various times in various countries. One approach was to offer a subsidy in the form of either a reduced price for the product or a payment based on estimated energy reduction after installation. Another approach, widely used by government agencies, is a combination of labelling and publicity. The idea is to make energy-efficient lighting products easy to identify and specify (Nirk, 1997; Howarth et al., 2000). Neither was very effective. Basically, the problem was that the incandescent lamp was seen as a commodity, whereas the compact fluorescent was seen as an investment. This, when combined with the slow warm-up time and the rather indifferent colour properties of the compact fluorescent, was enough to ensure that compact fluorescents were more frequently seen in hotels than in homes.

Persuasion having failed, governments around the world have recently decided on compulsion by arranging for the incandescent lamp to be withdrawn from the market. The process started with the highest wattages with the wattage limit gradually being reduced until virtually all general service incandescent lamps will soon have disappeared from the market. These actions produced a vociferous but largely ineffective response from people who resented the interference of government in what had been a matter of the householder's choice as well as from those with concerns about the health and environmental impacts of a much increased use of compact fluorescent lamps. And this is not the end of attempts to rid the world of inefficient light sources. Several countries have proposed that by the end of this decade only light sources with luminous efficacies above 45 lm/W will be allowed. All of the aforementioned has been achieved with the support of the lighting industry which has seen an opportunity to significantly increase the market for its more expensive compact fluorescent and LED light sources.

Given the governing elites' indifference to the views of the people in so many countries, including many democracies, it is unlikely that this trend for proscribing inefficient but popular light sources will be reversed any time soon. But why has the desire to reduce electricity demand been focused on the incandescent lamp when there are so many other forms of electricity excess evident to anyone who cares to look around? There are six answers to this question. First, lighting is a significant component in domestic electricity consumption, typically about 18% globally, and domestic electricity consumption represents about 31% of all electricity consumption by lighting (IEA, 2006). Second, in many countries, the most popular light source used in the home is the incandescent lamp. Third, light is a conspicuous consumer of electricity, so by changing its form, a government can be 'seen' to be doing something about climate change. Fourth, changing lighting in the home is easy. It simply requires changing one light source for another without necessarily changing the luminaire or rewiring. Fifth, more efficient light sources already exist. Sixth and most importantly, the costs of the required changes fall on the householder. Other users of electric lighting in commerce and industry are well aware of the lifetime costs of different light sources which is why light sources with higher luminous efficacies, such as discharge and solid state light sources, are already widely used in these applications.

It is important to note that regulations on power density or luminous efficacy do not really address energy because they fail to consider the hours of use of the installation. There are moves in the United Kingdom to adopt the lighting energy numeric indicator (LENI) as the basis for the next round of changes to the building regulations (SLL, 2012a). LENI originates from the BS EN 15193:2007 (BSI, 2007b) and quantifies the total amount of energy to be used by a lighting system per square metre per year. The advantage of this approach is that it actually addresses the purpose of the policy behind the regulations, to reduce electricity consumption. It will be interesting to see if this obvious next step is taken and, if so, what impetus it gives to the take-up of sophisticated control systems.

While such regulations can be considered the 'stick' elements of a system intended to reduce electricity consumption by lighting, there are also 'carrot' elements. These consist of attempts to encourage good energy-efficient design by providing targets to be met and publicity for those achieving them. In the United Kingdom, buildings occupied by public authorities and institutions providing services to the public that have a floor area greater than 1000 m^2 have to display a certificate indicating the energy rating on a simple alphabet scale based on the annual energy consumption of the building. Whether or not this certificate is displayed in a prominent place and if many members of the public understand what it means is unclear.

More meaningful 'carrots' are likely to be the Building Research Establishment Environmental Assessment Method (BREEAM) and the Leadership in Energy and Environmental Design (LEED) schemes developed in the United Kingdom and United States, respectively. These are aimed at professionals, and participation is voluntary. Both schemes assess many energy aspects of a building as a whole and allocate a number of points for each aspect. Both daylighting and electric lighting are part of the assessment. Based on the percentage of points available, the building can be categorized on a scale ranging from outstanding to unclassified. In the same way that there are no no-star hotels, there is no 'fail' category. Nonetheless, owners of buildings classified as outstanding or excellent can parade their environmental credentials and designers of these buildings can seek business on the basis of their achievements. The element of competition inherent in such endorsements helps to promote initiative and ingenuity in design, including lighting design.

16.4 TRENDS IN LIGHTING RECOMMENDATIONS

Lighting recommendations are produced by many different bodies in many different forms (SLL, 2009, 2012a; IESNA, 2011a). Whatever their form, the primary role of all such documents is to ensure that the lighting provided is suitable for its purpose. Different applications have different purposes and hence give different weights to different aspects of lighting. For industrial lighting, the main priority is for the lighting to enable people to work quickly, easily and accurately. For the lighting of a hotel foyer, the impression created is the first priority. For large sports stadia, often the purpose is to ensure that television cameras can record the action in slow motion. Thus, the recommendations for different applications can be expected to contain different criteria and different levels of the same criteria. This is made manifest in the latest edition of the IESNA Lighting Handbook (IESNA, 2011a) where guidance is offered on 17 different application areas, each area containing numerous subdivisions. For each area, there is a large table specifying illuminances recommended for horizontal and vertical planes as well as illuminance uniformities. Qualitative advice is also given on glare, veiling reflections, flicker, colour rendering, etc. What is not given is any quantitative advice on maximum levels of energy consumption by lighting. Instead, there is some discussion of when various types of control system might be used and reference to whole-building standards (ASHRAE, 2007). This is rather odd because, for a given light source and luminaire, the illuminances to be provided strongly influence the maximum power demand of the installation. Further, the relationship between illuminance and power demand is almost linear, while once well up on the plateau of visual performance (see Section 4.3.5), quite large changes in illuminance produce minimal changes in visual performance. This is important because it suggests that the quickest, simplest and cheapest way to reduce electricity consumption by lighting is to reduce the recommended illuminances.

Given this possibility, it is interesting to consider how illuminance recommendations have changed over the years. Mills and Borg (1999) reviewed the illuminance recommendations made in 19 different countries and found wide differences between different countries in the illuminance recommended for the same application. From their review, Mills and Borg (1999) concluded that the historical pattern has been for recommended illuminances to increase from about 100 lx in the 1930s to 500–1000 lx in the early 1970s after which they stabilized or declined to around 500 lx. The early 1970s was the time of the first world energy crisis based on a dramatic rise in the price of oil. The current trend in illuminance recommendations is towards a divergence and a convergence. The divergence occurs because there is a tendency to recommend a range of illuminances rather than a single value for such applications as offices based on the many different means by which information can now be presented. The convergence occurs because a similar range of illuminance (300–500 lx) is now recommended in many different countries.

This variability in illuminance recommendations causes some conspiracy theorists to be suspicious of undue commercial influence. The question they ask is ‘If about 100 lx was sufficient for offices in 1936, why is 500 lx regarded as necessary today?’ The answer to this question is that today is not 1936. The capabilities of the human visual system have not changed since 1936, but the nature of office work has changed, the means of providing light have changed, the furnishing of offices has changed and, most importantly, people’s expectations have changed.

The changes in lighting recommendations over time reveal a fact about all lighting recommendations that should always be remembered. Lighting recommendations are not immutable. They are not like the laws of physics nor are they written on tablets of stone. Rather, they represent the best efforts of people to decide on reasonable lighting recommendations in the prevailing conditions. To reach this decision for any particular application, a number of factors have to be considered. First, there are what might be called the aims of the lighting. For each application, it is necessary to consider the relative weights to be given to task visibility, task performance, observer comfort and perceived impression. Once the aims of the lighting have been specified, the necessary lighting conditions can be derived from any available experimental evidence and from practical experience. Second, there is the extent to which the lighting desired can be achieved with available equipment. There is little point in recommending lighting that cannot be achieved. Third, the economics need to be assessed. What does it cost to produce the recommended lighting from the available equipment? There is little point in recommending lighting that is not economically viable. These three factors – the desired lighting, its technical possibility and its cost to produce – are all considered before making a decision about lighting criteria. The point to grasp from all this is that recommended illuminances, and all other quantitative lighting criteria, are matters of judgment, involving the balancing of several factors. Therefore, they inevitably represent a consensus view of what is reasonable for the conditions prevailing when they are written (Boyce, 1996). That consensus will be different in different countries, and different at different times in the same country, depending on the state of knowledge about lighting, the technical and economic situation and the interests of the people contributing to the consensus. Thus, it would certainly be possible to make a case for a lowering of current illuminance recommendations based on the need to reduce electricity consumption.

At the moment, most lighting recommendations are basically elaborations of illuminance tables (IESNA, 2011a; SLL, 2012a). True, there have been attempts to move attention away from the horizontal working plane by claiming that illuminance recommendations apply to the task plane, wherever that may be and by adding vertical or cylindrical illuminances as an additional requirement (BSI, 2011a; IESNA, 2011a), but without changes to the design process so that designers know where the tasks will be and what type of lighting they require, these changes seem unlikely to make much difference. The fact is the design of lighting for workplaces is often an exercise in prediction based on assumptions. Fortunately, providing the recommended illuminance uniformly across a horizontal plane in a room with high-reflectance walls and ceiling will usually provide adequate if indifferent lighting for many applications, provided care is taken to avoid glare and to have a modicum of upward light. This is probably why the assumption of a horizontal working plane has survived in design despite many years of exhortation for its abolition by experienced designers seeking to make lighting more interesting.

Now, however, there is a much more radical approach being suggested. This starts by undermining the fundamental purpose claimed as the basis for illuminance recommendations, to ensure adequate visibility. Cuttle (2010) argues that, over the last 30 years, many visually difficult tasks, for example, reading a fifth carbon copy, have disappeared and, where they do occur, technology often provides a better way of either doing the task or making it more visible than simply increasing the illuminance. Further, more and more information is being viewed on self-luminous devices such as smartphones and computer screens which higher illuminances make it more difficult to see. He concludes that current lighting recommendations based on providing enough light to ensure task visibility on a horizontal working plane cannot be justified. As a replacement, he suggests that the basis of lighting recommendation should be changed to providing something he calls ‘perceived adequacy of illumination’. This rather begs the question ‘adequate for what?’ My answer would be ‘for anything that I would expect to do in this space’ which basically means I am judging the brightness of the space. The metric he associates with this criterion is mean room surface exitance as measured from the position of the observer’s eyes. This metric ignores direct light from the luminaires and considers only light reflected from the room surfaces. Adopting mean room surface exitance as a basis for lighting recommendations would have some interesting implications because light distributions that illuminate the walls and ceiling then become much more energy efficient than those that concentrate their output onto the horizontal plane. Cuttle (2013) has recently gone further by suggesting an additional criterion called target/ambient illumination ratio and a design procedure for first lighting the space and then any significant objects in it. This procedure is all-encompassing in that it allows both art galleries and speculative office space to be designed by the same process, although the former will result in very different lighting than the latter. Interestingly, uniform illumination of a horizontal working plane can occur but now it will be the result of a considered opinion rather than unthinking obedience to a schedule of illuminance recommendations. Such proposals are intellectually rigorous but seem to be focused on the wrong question. If Cuttle (2010) is correct in claiming that ensuring visibility is no longer the prime purpose of lighting, and there is a lot of truth in what he says, it will be interesting to see how long it is before someone in authority who is concerned about electricity consumption is knocking on the door of those who publish lighting recommendations wanting to know how the current illuminance recommendations can be justified and why they should not be reduced.

16.5 DESIGN

Ultimately, all that the attempts to limit electricity consumption discussed earlier amount to are pieces of paper. To actually limit electricity consumption by lighting, it is necessary to choose the right design approach and to use the right technology. There are three current trends in lighting design for interiors that have important implications for electricity consumption. The first is the emphasis in recent lighting recommendations (BSI, 2011a) given to the fact that the recommended illuminances are for the task area only and not necessarily for the whole space. The implication is that a task/ambient lighting approach should be adopted rather than providing the same task illuminance uniformly everywhere. In the task/ambient approach, the illuminance used for ambient illumination will be much lower than that recommended for task areas so the electricity consumption of the whole installation should be much lower than when a uniform lighting installation is used. The second is the growing interest in making more use of daylight in buildings (Mardaljevic et al., 2009). This is believed to be good for avoiding circadian disruption and for reducing electricity consumption, provided the amount of daylight is controlled to avoid overheating and visual discomfort and the electric lighting is fitted with appropriate controls to switch off or dim it when there is enough daylight. The third is the advocacy of control systems, sometimes to avoid the waste inherent in lighting an area when no one is present and sometimes to provide an element of individual control of lighting. This last point is believed to be effective in reducing electricity consumption because there are large differences in individual preferences for illuminance (Maniccia et al., 1999; Boyce et al., 2000a; Moore et al., 2003) so providing some individual control would allow people who prefer a lower illuminance than the maximum provided to dim the lighting.

Of course, these trends are superimposed on the well-established energy efficiency considerations involved in the choice of light source and luminaire. Different light sources have different luminous efficacies (see Table 1.4) so choosing an energy-efficient light source is always desirable, provided it meets other requirements such as appropriate colour properties. The next consideration is the choice of luminaire where efficiency is given by luminaire light output, this being the proportion of the light source luminous flux that escapes from the luminaire. Consideration also has to be given to the luminaire luminous intensity distribution to ensure that light is distributed where desired. Once an appropriate layout has been selected, the result of these choices will be a fixed lighting installation usually controlled by a simple switching system. Designers and purchasers of lighting installations are well aware of the importance of electricity consumption to the costs-in-use of lighting installations so this is almost always a point that will be considered. The question that now needs to be addressed is how much electricity consumption can be reduced when task/ambient lighting with appropriate controls is used in a building with plenty of daylight available?

A partial answer to this question can be found in Moore et al. (2003). In this study, the patterns of use of electric lighting in four office buildings in the United Kingdom were monitored for almost 2 years. The offices were all open plan and the lighting consisted of daylight through windows and a regular array of recessed louvred luminaires fitted with fluorescent lamps, the luminaires being controlled in groups varying in size from 1 to 9. The people sitting underneath each luminaire group could dim the luminaires over various ranges or switch them off as desired using either hand-held or column-mounted IR transmitters or by telephone. In the four offices, the electricity consumption by lighting was reduced to 54% of the maximum, individual buildings covering a range of 39%–74%. These reductions in electricity consumption serve to illustrate the potential of one form of control but little more. The use of multiple luminaires under one controller means that several people are likely to be involved in the choice of illuminance so it can hardly be called individual control. Also, the possible range of dimming was different for each building as was the method of control.

A more complete answer to the question posed earlier can be found in a study by Galasiu et al. (2007). In this study, measurements of electricity consumption by lighting were made on 4 floors of a rectangular, 12-storey, curtain-walled, green-tinted glazed office building in Burnaby, British Columbia, Canada. Each floor was mainly furnished as open-plan offices with cubicle workstations, the windows being fitted with conventional venetian blinds. Each workstation had a direct–indirect luminaire suspended over it. Each luminaire contained three 32 W fluorescent lamps, an occupancy sensor and a light sensor and was connected to a central control computer. Of the three lamps, one directed its light output mainly upwards for ambient lighting while the other two directed their light output mainly downwards for task lighting. The upward lamp was kept at full light output between 07.30 and 17.00 h but switched off outside these hours unless occupancy was detected. The two downward lamps were controlled in three different ways. Occupancy control ensured that when the workstation was empty, the lamps gradually dimmed to the off state. When presence was detected, the lamps were immediately restored to the previous light output set by the occupant of the workstation. Daylight was allowed for by a light sensor that monitored the surrounding illuminances and dimmed the lamps to 50% light output when sufficient light was available from daylight or other surrounding electric lighting to maintain the illuminance desired by the occupant of the workstation. This limit of 50% light output could be overridden by individual control in the form of an on-screen slider located on the occupant's desktop computer that allowed both on/off switching and dimming. At full light output, the electric lighting installation produced an illuminance of 450 lx at the centre of the workstations and had a power density of 5.8 W/m^2. Data on patterns of use were available from 86 workstations of which 57 were workstations adjacent to the windows, 18 were in the next row in, this being some 2.5–4.5 m from the window, and the remaining 11 were in the core of the building more than 5 m from a window. These recordings were made over 1 year in three phases. In phase 1 (39 workdays), control was limited to the occupancy sensors and the on-screen individual controls. The occupancy sensors operated with a delay of 8 min followed by 7 min of dimming to switch off. In phase 2 (140 workdays), all three control systems were active, the occupancy sensors having a delay of 12 min followed by 3 min of dimming to switch off. In phase 3 (61 workdays), the controls were operated as in phase 2 but the workers were sent an e-mail once a month to remind them of the individual control facility and to encourage them to save energy. These measurements showed the measured average daily energy savings per luminaire relative to the same installation operating at full light output for the total daily work hours: 39%, 47% and 42% in phases 1, 2 and 3, respectively. An open-plan office in one-half of one of the measured floors was equipped with a more conventional uniform installation consisting of a regular array of recessed parabolic louvre luminaires fitted with two fluorescent lamps and controlled by zoned on/off switches. At full light output, this conventional installation produced about 400 lx at the centre of the workstations and had a power density of 10 W/m^2. In phase 2, the average daily energy savings per luminaire for the installation equipped with individual control relative to this more conventional installation was 68%.

Clearly, it is possible to reduce electricity consumption by a significant amount with task/ambient lighting and correctly commissioned controls, but how much does each design element contribute to the savings? From the installed power densities given earlier, it is apparent that adopting the task/ambient approach without controls reduces electricity consumption by 42% relative to the conventional fixed uniform lighting assuming the same hours of use. As for the different control systems, by making assumptions for different combinations of controls, for example, for occupancy sensors alone, it was assumed that the downward component of the lighting would have been used at full power whenever the workstation was occupied and been off at all other times. Galasiu et al. (2007) were able to estimate the percentage energy savings relative to the task/ambient lighting at full power for the same hours of use. Table 16.1 shows the estimated average percentage daily energy savings for all three types of control, separately and in various combinations, in all three phases of the study. Examination of Table 16.1 suggests that the occupancy sensors are the most effective at saving energy and the individual controls are the least effective with the light sensors lying somewhere between. It is important to recognize that this order may be specific to this installation. If people rarely leave their workstations, occupancy sensors will save very little energy. Similarly, if there is little daylight, light sensors will save little energy. However, individual controls should be effective everywhere because their adjustment is driven by individual preference for illuminance regardless of how it is provided.

So far so good, but how do the occupants of the workstations evaluate the lighting? The answer to this question can be found in Veitch et al. (2010). At the same time as the energy use was being recorded, a series of questionnaire surveys were being carried out in the same open-plan offices aimed at discovering the occupants' assessments of the lighting, their satisfaction with the environment and their level of job satisfaction. The surveys were conducted twice in phase 2 and once

TABLE 16.1
Average Percentage Daily Energy Savings Produced by Different Control Systems Relative to the Energy Consumption of the Same Lighting Installation Operating at Full Light Output in Three Phases of the Study

Control System	Energy Savings Phase 1	Energy Savings Phase 2	Energy Savings Phase 3
Occupancy sensors	29	35	38
Individual control	20	11	5
Light sensors	—	20	11
Occupancy sensors + individual control	40	40	39
Occupancy sensors + light sensors	—	45	44
Individual controls + light sensors	—	24	14
Occupancy sensors + individual controls + light sensors	39	47	42

Source: Galasiu, A.D. et al., *Leukos*, 4, 7, 2007.

in phase 3. Assessments of the lighting are what are of interest here, the instrument used being based on the office lighting survey developed by Eklund and Boyce (1996). Table 16.2 summarizes the percentages agreeing with each statement in this survey for the group with the battery of controls, including individual control, and those working under the conventional uniform lighting with only zonal switching. Table 16.3 shows the percentage of occupants with the battery of controls and those with conventional lighting answering the question 'How does the lighting compare to similar workplaces in other buildings: worse, the same or better?' Examination of Table 16.2 reveals that there are a number of statistically significant differences between those with controls and those without in the first and third times the survey was administered but not the second time. This can be explained by the months the three surveys were administered. The first survey was done in April and the third in November, while the second was done in August. Given the extensive daylighting in the offices, it is likely that in August the electric lighting would have had little impact but it would have had much more in April and November. Therefore, looking only at the first and third times the survey was done, it can be seen that more occupants with controls considered the lighting comfortable and fewer considered the lighting too bright and poorly distributed. Table 16.3 supports the conclusion that the lighting with controls is considered better than conventional uniform lighting controlled by zonal switching. This implies a win/win situation in that task/ambient lighting with controls not only reduces energy consumption but is also considered better than uniform lighting with zonal switching.

Given this conclusion, it is interesting to consider why task/ambient lighting and controls are used so infrequently. One answer is that for task/ambient lighting to be used, it is necessary to know what the tasks are likely to be and where there will be located. Such information is not likely to be available when the building is to be let to tenants. Even if it is for the owner's personal use, the rate at which interiors

TABLE 16.2
Percentage of Occupants in Open-Plan Offices with Workstation-Specific Lighting and a Battery of Controls (Controls) Agreeing with Various Statements about the Lighting Compared to the Percentage of Occupants Who Were Working under a Conventional Regular Array of Uniform Lighting with Only Zonal Switching (No Controls) Agreeing with the Same Statements

	Phase 2		Phase 2		Phase 3	
	Time 1		Time 2		Time 3	
Statement	**Controls**	**No Controls**	**Controls**	**No Controls**	**Controls**	**No Controls**
Overall, the lighting is comfortable.	90	72*	95	87	94	75*
The lighting is uncomfortably bright for the task that I perform.	5	22*	5	7	3	20**
The lighting is uncomfortably dim for the task that I perform.	6	17	6	7	12	5
The lighting is poorly distributed here.	11	22*	6	20	12	35*
The lighting causes deep shadows.	6	6	2	7	6	15
Reflections from the light fixtures hinder my work.	0	22***	5	7	5	10
The light fixtures are too bright.	6	17	2	13	2	20**
My skin is an unnatural tone under the lighting.	6	6	2	13	9	20
The lights flicker throughout the day.	2	22**	0	7	0	5

Source: Veitch, J.A. et al., Office occupants' evaluations of an individually-controllable lighting system, IRC Research Report 299, National Research Council Canada, Institute for Research in Construction, Ottawa, Ontario, Canada, 2010.

Note: The statements were asked at three different times. Statistically significant differences between the two types of lighting are marked $^{*}p < 0.05$ or $^{**}p < 0.001$ or $^{***}p < 0.001$ in the no control column.

are rearranged can also be a disincentive as the lighting will have to be moved every time the work layout is changed. Developments in wireless communication and computer optimization may eventually overcome this problem by making it possible for a regular array of luminaires to be adjusted to provide individual preferred illuminances at minimum electricity consumption without moving luminaires when the workstations are moved (Wen and Agogino, 2011), but until they do, energy saving by task/ambient lighting is likely to remain potential rather than actual.

TABLE 16.3
Percentage of Occupants in Open-Plan Offices with Workstation-Specific Lighting and a Battery of Controls (Controls) Answering the Question 'How Does the Lighting Compare to Similar Workplaces in Other Buildings: Worse, Same or Better?' Compared to the Percentage of Occupants Who Were Working under a Conventional Regular Array of Uniform Lighting with Only Zonal Switching (No Controls) Answering the Same Question

How Does the Lighting Compare to Similar Workplaces in Other Buildings?	Phase 2		Phase 2		Phase 3	
	Time 1**		Time 2*		Time 3**	
	Controls	No Controls	Controls	No Controls	Controls	No Controls
Worse	5	28	2	13	3	35
Same	30	61	32	67	40	40
Better	65	11	66	20	57	25

Source: Veitch, J.A. et al., Office occupants' evaluations of an individually-controllable lighting system, IRC Research Report 299, National Research Council Canada, Institute for Research in Construction, Ottawa, Ontario, Canada, 2010.

The question was asked at three different times. Statistically significant differences between the two types of lighting are marked $^{*}p < 0.001$ or $^{**}p < 0.001$.

Controls also suffer from insufficient information. If the pattern of use is unknown, the potential energy savings of occupancy sensors is unknown. But controls also suffer from their notorious past. Unless carefully arranged and commissioned, occupancy controls can cause annoyance because of lighting being turned off when the space is occupied, particularly when the lighting is switched rather than dimmed. Similarly, daylight harvesting has a reputation for being ineffective because when applied to large areas of uniform lighting, the trigger level has to be set so high to avoid complaints that little energy is saved but when applied to small areas there is little energy to save.

As for individual control, Galasiu et al. (2007) found that individual lighting controls alone would have produced the least energy savings and if added to a system already controlled through occupancy sensors and light sensors would have provided very little by way of additional energy savings. Further, recordings of the number of adjustments made using the individual control showed that these controls were used rarely in all three phases of the study once the occupants had set their preferred level. And yet, comments made by the occupants in the surveys described by Veitch et al. (2010) indicated that having individual control of the amount of light on the workstation was considered a valuable feature of the lighting. Others have found a similar opinion (Moore et al., 2002a). It is not that many people want to be able to continuously adjust the lighting on their work but that there are large differences in individual preferences for illuminance. These trends are evident in a field simulation experiment conducted using a similar cubicle-furnished office lit with the same type of task/ambient lighting

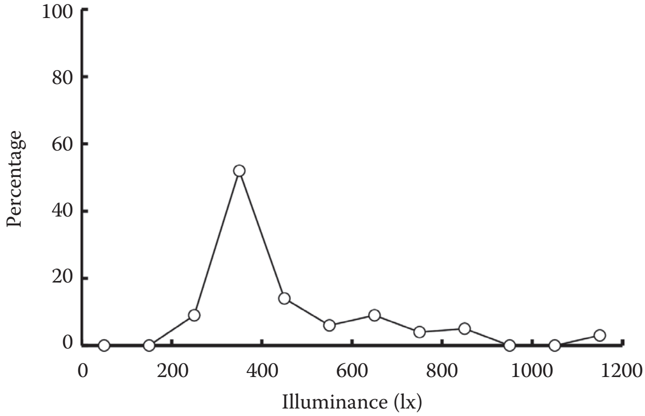


FIGURE 16.2 Percentage of office workers choosing to work at different illuminances in 100 lx bins. (After Boyce, P.R. et al., *Lighting Res. Technol.*, 38, 358, 2006a.)

with individual control through a computer screen but with little daylight (Boyce et al., 2006a,b). The participants in the study worked for 1 day in the office doing a wide variety of tasks. The individual control of the downward component of the luminaire suspended over the workstation was used at the beginning of the day to set the desired illuminance as shown by the fact that 82% of the illuminances used at the end of the day had been set at the beginning. Further, different people chose very different illuminances. Figure 16.2 shows the distribution of the percentage of participants opting to work at different illuminances measured at the end of the day. The average desktop illuminance could range from 275 to 1075 lx and the whole range was used. This finding implies that individual control of illuminance is valued not for its ability to save energy nor for the ability to match the illuminance to the task but rather because it allows the occupant some control over their own environment. Veitch et al. (2010) found that having individual control and, to a lesser extent, proximity to a window had a positive effect on satisfaction with the environment, and satisfaction with the environment and overall environmental satisfaction has been found to be linked to job satisfaction and organizational commitment (Carlopio, 1996).

What all this implies is that even in circumstances where individual control of the lighting is of limited value for reducing electricity consumption by lighting, it is of major value for increasing satisfaction with the lighting and the working environment with consequences for job satisfaction, something that may be of greater value to an organization then energy saving. But if your focus is on reducing electricity consumption by lighting, design offers plenty of opportunities to achieve this aim through choices of lighting type, light source, luminaire, layout and the judicious use of controls. The obstacles to the implementation of energy-saving lighting design are inadequate information about the visual environment to be created, lack of flexibility in changing the design after installation and the additional costs that may be incurred over and above the financial saving associated with reduced electricity consumption. Until these obstacles are reduced, it is likely that design as a means to reduce electricity consumption by lighting will remain a minority interest.

All the previously mentioned has been focused on reducing electricity consumption by lighting in interiors, but there is also considerable interest in achieving the same objective for road lighting (Boyce et al., 2009). The most basic approach has seen local authorities switching off road lighting from midnight to 05.00 h. This has been justified by arguing that lighting is unnecessary at these times because there are few pedestrians about and traffic densities are much lower. Whether or not turning off the road lighting for these hours will lead to an increase in deaths remains to be seen. The data discussed earlier that show the beneficial effects of having light at night on pedestrian fatalities and injuries (see Section 10.4.4) were collected through the evening hours rather than late at night and the demographics of drivers late at night may be very different from those about in the evening.

A more sophisticated approach is possible through remote monitoring of road lighting luminaires. This is done using either mains signalling or wireless communication to connect a large number of luminaires to a local transmitter that in turn is linked to a central server through a mobile phone network or by landline. The central server provides a web portal through which authorized individuals gain access to monitor and control the road lighting network. Monitoring of the status of each luminaire allows failures, including wasteful daytime burning, to be identified and rectified quickly. When combined with dimming control gear, remote monitoring also offers the possibility of adjusting the amount of light used for road lighting according to the traffic flow and weather conditions. At present, the most usual approach to control road lighting is step dimming with slow transitions between each step. Using such remote control systems has resulted in energy savings in the range 25%–45% in the United Kingdom, China and Finland (Guo et al., 2007; Walker, 2007).

The ultimate development in such controls is the combination of fast dimming LED lighting with sensors that can detect the presence of people or vehicles on the road (Haans and de Kort, 2012). The idea is that the luminaires are only set to full light output as they track the movement of the person or vehicle along the road, returning to a dimmed state after the person or vehicle has passed. How acceptable this will be to pedestrians and drivers remains to be seen.

Regardless of the control system used, the longer the time spent operating in a dimmed state, the less will be the electricity consumption of the road lighting. Such control systems undoubtedly increase the first costs of an installation but, when used as described, should markedly reduce electricity consumption and hence operating costs and life cycle costs. Whether or not such savings are enough to justify the investment in financial terms is a question that will always have to be considered.

16.6 LOAD SHEDDING

So far, this chapter has been devoted to methods for reducing electricity consumption by lighting long term, the motivation for this being both financial and environmental. But sometimes, there is a more urgent need to reduce electricity demand. On occasions, both developed and underdeveloped countries can suffer from demands for electricity close to their maximum generating capacity. When this happens, something has to give, either more generating capacity has to be accessed or demand has to be reduced. If these alternatives do not occur, there is the possibility of a network collapse. This can often be avoided if there is a system for reducing power demand, on demand. This is known as a demand response or, more colloquially, load shedding or peak lopping. In this, large users of electricity agree to reduce demand rapidly should the electric utility call for it. Such agreements are usually reached in exchange for a price reduction of some form. Lighting is an attractive option for load shedding as peak demand often occurs in late afternoon when outdoor temperatures are at their height and air conditioning is operating at full power. At this time, there is often plenty of daylight available and, even where it is not available, the electric lighting can often be dimmed. Of course, such dimming will worsen the visual conditions for people working so the question naturally arises how acceptable will such a reduction in illuminance be. The answer depends on whether or not the reduction is detected and, if it is, how that reduction is perceived. If it is perceived as a short-term necessity required to ensure continuity of electricity supply, then acceptance will be high. However, if it is perceived as being a long-term attempt to save the company money at the expense of the workers' conditions, acceptance will not be high. In this situation, it would be better if the reduction in illuminance was not detected at all. This raises the question as to how much an illuminance can be reduced without people working under it noticing.

A number of laboratory studies have examined this question. Akashi and Neches (2004) put people into a windowless room and dimmed the illuminance slowly and smoothly. They found that when the observers were engaged in a visual task, only 50% detected a 15% change in illuminance and 80% considered a reduction of 20%–30% acceptable. Newsham and Mancini (2006) carried out a day-long study in a simulated office with little daylight. At the start of the day, the participants were allowed to adjust the illuminance on their desks to their preferred level, the mean setting being 450 lx. At the beginning of the afternoon session, an unannounced slow and smooth reduction in the illuminance on the desk was initiated. As a result of this dimming, the minimum desktop illuminance that could be achieved was 225 lx. The participants did not know that changes would be made in the lighting but they could intervene to increase the illuminance on the desk at any time. Only 17 out of 30 participants intervened. Figure 16.3 shows a cumulative frequency distribution of percentage illuminance reduction when intervention was possible. For the 17 participants who intervened, the percentage illuminance reduction is measured from the individual preferred illuminance to the illuminance at which they intervened. For the 13 participants who did not intervene, the percentage illuminance reduction is measured from the individual preferred illuminance to the minimum illuminance following dimming to 225 lx. Fortunately, the part of Figure 16.3 that is of interest for the purpose of setting limits for load shedding is the low-frequency end of the cumulative frequency where a few people start to intervene. Figure 16.3 shows that only three participants (10%) had intervened by the time the illuminance on their desks had decreased by 18% from their preferred level. Figure 16.4 shows the cumulative frequency distribution of the times at which the 17 participants intervened to change the desktop illuminance measured from the start of the illuminance reduction. Three (10%) participants intervened within about 25 min of the start of the dimming. These results suggest that significant load shedding without complaint is possible but load shedding has to be an emergency response to reducing maximum demand, not a permanent situation.

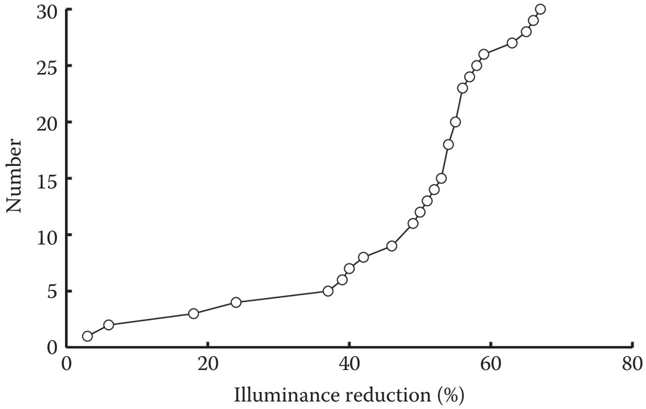


FIGURE 16.3 The cumulative frequency distribution of the percentage illuminance reduction for load shedding when intervention was possible. For the 17 participants who did intervene, the percentage illuminance reduction is measured from the individual preferred illuminance to the illuminance at which intervention occurred. For the 13 participants who did not intervene, the percentage illuminance reduction is measured from the individual preferred illuminance to the minimum illuminance following dimming for load shedding. (After Newsham, G.R. and Mancini, S., *Leukos*, 3, 105, 2006.)

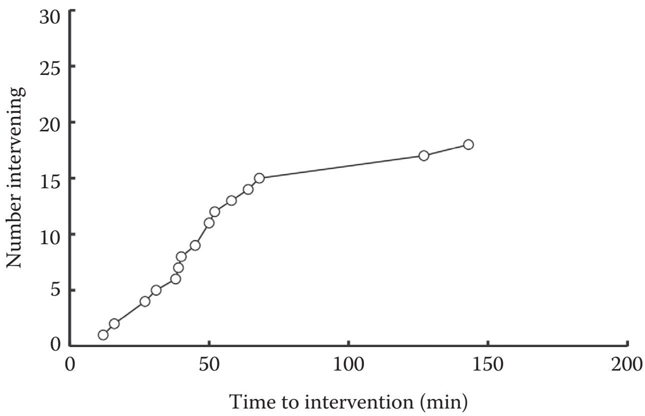


FIGURE 16.4 The cumulative frequency distribution of the 17 participants intervening to change the desktop illuminance at different times after the start of the load shedding illuminance reduction. (After Newsham, G.R. and Mancini, S., *Leukos*, 3, 105, 2006.)

Both these studies were done in rooms where there was no or little daylight. Newsham et al. (2008) dimmed electric lighting from 400 lx over 10 s in an office with and without daylight. Without daylight, the percentage reduction in the illuminance provided by the electric lighting that was not noticed by the occupants was 20%, but with daylight, it rose to 40%–60%. This is as it should be because the daylight buffers to some degree the reduction in the illuminance provided by the electric lighting. All the above have been laboratory studies. Fortunately, Newsham and Birt (2010) carried out a field study in an open-plan office with 330 dimmable luminaires and on a college campus with 2300 dimmable luminaires in several buildings, over the months of May–July. In the office, the lighting was dimmed by up to 35% over 15–30 min on two afternoons resulting in power reductions of 23%–24%. On the campus, three afternoon load shedding trials were held in which the lighting was dimmed by up to 40% resulting in power demand reductions in the range 14%–18%. In both locations, people were aware that a load shedding experiment was in operation during the summer but had no idea when the power reductions would take place. Despite there being a familiar way for people in the office and on the campus to complain about the reduced illuminances, no lighting-related complaints were received by facilities management throughout the afternoons of the trials. Clearly, lighting provides a simple route for reducing electricity demand in the face of an approaching system emergency. Newsham and Birt (2010) suggest a two-stage process. The first stage is dimming by amounts that are unlikely to be noticed, these being 20% where there is no daylight, 40% where there is little daylight and 60% where there is a lot of daylight, all for a 10 s dimming time. The second stage is dimming that will be noticed by a significant proportion of people but will still be acceptable to a majority. For a 10 s dimming time, these levels are 40% with no or little daylight and 80% where there is a lot of daylight.

16.7 SUMMARY

Electricity is by far the most common form of power used for lighting. The generation of electricity often involves the burning of fossil fuels which itself sends carbon dioxide into the atmosphere. The end results of the accumulation of carbon dioxide in the atmosphere are believed to be global warming and climate change. Lighting is a major consumer of electricity. It is also thought to be one application where demand might be considerably reduced. This is because lighting installations have relatively short lives compared to buildings, are easy to access and there already exist energy-efficient technologies that are not widely used.

Regulations that have legal force have long been used to ensure the health and safety of the public, but now they are also being used to reduce electricity consumption by lighting. These regulations take two forms. One consists of specifying a maximum lighting power density to be used in buildings and outdoors. The result has been a steady reduction in the lighting power densities used in commercial buildings. The other consists of removing energy-inefficient products from the market by specifying minimum luminous efficacies for light sources. Such market manipulation has been a regulatory tool for many years but only recently has this become evident to the general public. This is because it has now been applied to the light source used by almost everybody at home, the incandescent lamp. Within a few years, it is hoped that the majority of light sources used in the home will be compact fluorescents or, more likely, LEDs.

It is worth noting that regulations on power density or luminous efficacy do not really address energy because they fail to consider the hours of use of the installation. One alternative that does is the LENI. This quantifies the total amount of energy to be used by a lighting system per square metre per year. The advantage of this approach is that it actually addresses the purpose of the policy behind the regulations, to reduce electricity consumption. It will be interesting to see whether or not this metric is ever adopted.

While regulations can be considered the ‘stick’ elements of a system intended to reduce electricity consumption by lighting, there is also a ‘carrot’ element. This element consists of a number of voluntary schemes designed to encourage good energy-efficient design such as the BREEAM and the LEED schemes developed in the United Kingdom and United States, respectively. These are aimed at professionals and participation is voluntary. Both schemes assess many energy aspects of a building as a whole and allocate a number of points for each aspect. Both daylighting and electric lighting are part of the assessment. Based on the percentage of points available, the building can be categorized on a scale ranging from outstanding to unclassified.

Lighting recommendations are produced by many different bodies in many different forms with various names such as codes, guides, recommended practices and handbooks. Whatever their form and name, the primary role of all such documents is to ensure that the lighting provided is suitable for its purpose. When they first appeared in the early twentieth century, lighting recommendations consisted of little more than a table of illuminances. Since then, they have grown to give quantitative advice on illuminances, glare, veiling reflections, flicker and colour rendering. What is not given is any quantitative advice on maximum levels of energy consumption by lighting. This is rather odd because, for a given light source and luminaire, the illuminances to be provided strongly influence the maximum power demand of the installation. Further, the relationship between illuminance and power demand is almost linear while once well up on the plateau of visual performance, large changes in illuminance produce minimal changes in visual performance. This is important because it suggests that the quickest, simplest and cheapest way to reduce electricity consumption by lighting is to reduce the recommended illuminances. This would certainly be possible because all lighting recommendations are matters of judgment, involving the balancing of several factors, among them being the economic and environmental costs of electricity generation.

Ultimately, all that the regulations, recommendations and endorsements that influence lighting practice amount to are pieces of paper. To actually limit electricity consumption by lighting, it is necessary to choose the right design approach and to use the right technology. There are three current trends in interior lighting design that have important implications for electricity consumption. The first is the emphasis given in recommendations to the task/ambient approach to lighting. The second is the growing interest in making more use of daylight in buildings. The third is the advocacy of control systems. Long-duration field studies have shown that it is possible to reduce electricity consumption by a significant amount with task/ambient lighting and correctly commissioned controls. Further, surveys of people working in the offices examined showed that the task/ambient lighting with controls was considered better than conventional uniform lighting controlled by zonal switching. Given this conclusion, it is interesting to consider why task/ambient lighting and controls are used so infrequently. One answer is that for task/ambient lighting to be used, it is necessary to know what the tasks are likely to be and where there will be located. Often, such information is not available. As for exterior lighting, it is cost and developments in technology that are driving attempts at energy saving. Reductions in local authority budgets have caused some to switch off road lighting from midnight to 05:00 h. More interestingly, new technology is making it possible to dim road lighting so that the illuminances provided can be varied depending on traffic densities, weather conditions and even the presence or absence of pedestrians or vehicles. How acceptable these changes are and whether or not they will increase road deaths and injuries remains to be seen.

Reducing electricity consumption by lighting is a worthy long-term aim but sometimes there is a more urgent need to reduce electricity demand. This often occurs when demand for electricity comes close to the maximum generating capacity so there is a risk of a network collapse. This can be avoided if there is a system for reducing power demand, on demand. This is known as load shedding. Lighting is an attractive electrical load for load shedding as peak demand occurs when there is plenty of daylight available and, even where it is not, the lighting can often be dimmed. Such dimming will worsen the visual conditions for people working so the question naturally arises as to how acceptable such a reduction in illuminance will be. The answer depends on whether or not the reduction is detected and, if it is, how the reduction is perceived. A number of laboratory and field studies in offices have shown that, provided the lighting is dimmed slowly and smoothly, significant reductions in illuminance, and hence in electricity demand, can be made without complaint.

It is unlikely that the pressure to reduce electricity consumption by lighting will be relaxed any time soon. This means that ingenuity and technological innovation will be called for from both the lighting industry and lighting designers to ensure that good quality lighting is provided at minimum electricity consumption. More ominously, it also suggests that questions are soon going to be asked about the basis of current lighting recommendations. Hopefully, this book will provide some of the answers.

17 The Way Ahead

17.1 INTRODUCTION

What follows is unlike previous chapters in that it does not deal with definitions or quantities or experimental results and their application. Rather, it gives my opinions as to the problems facing lighting today and what lighting research might contribute to their solution. Broadly, these problems can be associated with new technology, new knowledge, and growing concerns about the economic and environmental consequences of lighting. Each of these problem areas requires some input from lighting research, although that input will take different forms for different problems. What these forms might be and how the required research should be conducted and evaluated are discussed.

17.2 BACKGROUND

As in the Chinese wish, today is an interesting time to be involved with lighting, for a number of reasons. First, lighting practice is undergoing a major shift in technology. Over the last decade, solid-state light sources have moved from being almost exclusively used for signs and signals to becoming the light source of choice for illumination. Indeed, to look at the pages of many lighting magazines, it almost seems that the approach to lighting today could be characterized by the saying 'LEDs are the answer, now what's the question?' LED light sources now offer a combination of competitive luminous efficacy, very long life, and wonderful flexibility. Regarding this last, LED light sources allow the creation of luminaires in which not only can the light output be varied but the light spectrum and light distribution can also be changed. Combine this with developments in computer power and wireless communication and the possibility of lighting installations that can easily be adjusted to match prevailing conditions arises. Such systems are already being used in road lighting and it will not be long before they begin to appear in other applications.

Second, there has been an explosion of interest in the effects of lighting beyond visibility. Specifically, the discovery of the intrinsically photosensitive retinal ganglion photoreceptor and its role in the non-image-forming systems (see Chapter 3) has created a surge of interest in the role of light exposure for human health. Initially, it was thought that the visual system and the circadian system could be treated separately (Boyce, 2006), but further studies have revealed that they are interconnected at a number of levels and that the impact of the intrinsically photosensitive retinal ganglion photoreceptor extends far beyond the circadian timing system (Boyce, 2011). At the moment, it seems that adverse health outcomes of light exposure are mainly associated with circadian disruption, but if it could be shown that light exposure also had an effect on human health for people who have a normal circadian timing cycle, then the justification for lighting recommendations would be dramatically extended from simply providing visibility to ensuring both visibility and health.

In addition to these physiological effects of light exposure, there has been increased interest in the psychological effects. Studies of learning in schools (Sleegers et al., 2013), recovery from medical operations (Joarder and Price, 2013), and perception of brand identity (Schiekle, 2010) have all demonstrated that the form of lighting used can have beneficial or detrimental effects on desirable outcomes. These effects tend to be probabilistic rather than certain and are associated with specific situations. Nevertheless, in the given situation, they can be real enough and suggest that lighting has a consistent role to play in influencing behaviour.

Third, there has been increased interest in the collateral damage caused by lighting. The damage of most interest is the contribution of electricity consumption to carbon dioxide emissions. As discussed in Chapter 16, governments around the world are making efforts to reduce or at least limit the growth in electricity consumption, and lighting is a very obvious and convenient target. The result has been regulations designed to limit the power density of both indoor and outdoor lighting installations and to ban the use of energy-inefficient light sources. So far, such regulations have been based on changes in technology but sooner or later, the question is likely to shift to how current lighting recommendations can be justified.

The other area of concern is light pollution. Special interests have driven this concern, but, as discussed in Chapter 15, the need is for a balance to be struck between those who wish to see the stars at night and those who value the use of light at night for safety, security, business, and beauty. Even when such a balance is achieved, there is still much to be said in favour of designing lighting so that it places light where it is needed and when it is needed rather than sending it in all directions. Together, concerns about electricity consumption and light pollution are placing tighter limits on how lighting is designed.

17.3 PROBLEMS WITH NEW TECHNOLOGY

The emergence of solid-state lighting into the lighting mainstream has raised a number of issues for lighting metrics. The one that has been most comprehensively considered is that of colour rendering. The CIE general CRI has been found wanting in that the calculated values of this metric underestimate the acceptability and colourfulness of LEDs to people (CIE, 2007). Consequently, there have been several different attempts to develop new metrics for colour rendering (see Section 1.6) but, so far, there has been no international consensus on a replacement for CRI. There are three reasons for this. The first is that different metrics are based on different objectives. One set of metrics seeks to quantify colour fidelity and therefore compares the performance of one light source with that of a reference light source. Another set of metrics seeks to quantify the extent to which the light source increases the saturation of colours, something that does not require a reference. Yet, others are based on models of colour appearance, the memory of colours, and colour harmony. The second is the desire to reduce the complexity of colour perception to a single number rather than admit that two or more numbers are required. The third reason has little to do with science, much more to do with business. This is the reluctance of light source manufacturers to see the performance of existing products downgraded by the use of a metric other than CRI. Lighting research could contribute to establishing consensus in this area by investigating how well people understand various metrics, individually and in combination.

Two other controversies that have been reawakened by the arrival of solid-state lighting are metrics of discomfort glare and flicker. The problem with discomfort glare is that when solid-state lighting is used, the glare source can be an array of high luminance points. The luminance of the immediate surround then becomes important. The importance of this luminance to discomfort glare was known many years ago (Hopkinson, 1963) but has been widely ignored. More research to bring the luminance of the immediate surround into the standard discomfort glare calculations is needed (Sweater-Hickcox et al., 2013).

As for flicker, LEDs operate using DC, so standard AC electricity supplies have to be rectified before being applied to the LED. The fast response time of LEDs means that, depending on how well the rectification is done, the light output will be seen as stable or flickering. A number of studies have been carried out to measure the detectability and acceptability of different levels of light source instability under extreme conditions (Bullough et al., 2011a, 2012b) although little has been done with groups of people sensitive to flicker such as those who experience migraines regularly. Until it is, it will be difficult to achieve a meaningful metric for flicker.

The arrival of solid-state lighting has also encouraged developments in the field of controls. In principle, LED luminaires can be designed that allow the light spectrum and the light distribution to be changed on demand. The problem is that what range of changes in spectrum and distribution are useful or acceptable has not really been examined, nor has the rate at which such changes should be made, nor how they should be controlled. Based on the way in which illuminance is adjusted when people have individual control of their lighting, the suspicion is that the light spectrum and distribution would be changed rarely after initial settings are made. There is much work to do in this area.

17.4 PROBLEMS WITH NEW KNOWLEDGE

The primary problem with the rapidly developing knowledge about the effects of light exposure on human health is its emerging complexity (see Chapter 3). This complexity ranges from fundamental questions to questions of efficiency and application. The fundamental questions concern the interrelationships between the visual system and the non-image-forming system as well as the expansion of the connections between intrinsically photosensitive retinal ganglion cell and other parts of the brain (CIE, 2004e). There has also been some evidence that light exposure can be used as treatment for a range of mood disorders. This is a positive effect, but there is also the possibility of a negative effect, this being the impact of exposure to light at night on the development and growth of cancers.

The questions of efficiency relate to the spectrum, intensity, timing, and duration of exposure to light. There are now several models of the spectral sensitivity of the circadian system (Rea et al., 2012a), but there is only limited understanding of the intensity of exposure required to manipulate the circadian system. There is also some evidence that the recent history of exposure to light can influence the sensitivity of the circadian system. Other relevant questions are as follows: How far above threshold does the stimulus need to be to ensure a reliable effect? Are some parts of the visual field more important than others? Where does the reciprocity between intensity and duration of exposure break down? How important is the timing of light exposure? To date, almost all the work that has attempted to answer such questions has been focused on the circadian timing system, but light exposure affects other hormones besides melatonin and has consequences beyond the circadian timing system.

As for applications, there are two questions that need to be addressed before much progress can be made. The first is what are the common patterns of light exposure over 24 h in the real world. Answers to this question are needed in order to understand any differences between people in their response to light exposure. The second is whether humans are robust as far as light exposure is concerned. If they are, then it is likely that the benefits of light exposure will only apply to people who have a fragile circadian system or who live under a very restricted light profile. If they are not, then light exposure will be important for everyone, even the healthy.

Clearly, there is much still to learn about the effects of light exposure on human health. Research in this area will require the cooperation of both medical and lighting experts. It will also call for expertise in different areas ranging from molecular biology through electrophysiology to cognitive psychology and human factors. Such cooperation is necessary for an understanding of both the effects of light exposure and the mechanisms that produce them to be achieved.

Another area in which new knowledge is developing is that of environmental psychology. For many years, the twin foci of lighting research have been the effect of lighting conditions on visual performance and the avoidance of visual discomfort. The result has been a clear understanding of what needs to be done with lighting to ensure a high level of visibility without discomfort. As a result of this success, the attention of some researchers has moved to more remote relationships involving lighting but still with financial and social significance, such as the effect of lighting conditions on the prevalence and type of crime (see Chapter 12) and the impact of daylight in stores on retail sales (Heschong-Mahone Group, 1999a, 2003b; Heschong et al., 2002a). The problem with such studies is that although they can show a relationship between lighting and the measured outcome, they do not reveal the cause. Further, all the earlier examples have been done in the field, an arena in which it is notoriously difficult if not impossible to maintain experimental control.

Yet, other studies have been devoted to exploring the effect of lighting conditions on mood and behaviour (Boyce et al., 2006b; Hubalek et al., 2010; Johansson et al., 2011). These can be done in the laboratory where tight experimental control is possible but then the problem is that the context is one of an experiment in a laboratory not the real world. How people feel and how they behave depends on the situation in which they find themselves, so attempts to transfer the results of such studies to the real world may be misguided.

In defence of both field and the laboratory studies in this area, it could be said that many of the studies to date are proof of concept studies, that is, they seek to establish that lighting does have an effect on the specific outcome and therefore should be considered when studying all the factors. Unfortunately, this is just the first step on what is likely to be a long and tortuous path to a full understanding resulting in a model capable of quantifying the role of lighting. An example of such a development is the work of Veitch et al. (2008). This reports two laboratory studies using simulated office spaces in which temporary office workers did a range of office tasks over a day. Two statistical analyses of the data revealed a series of links which demonstrated that people who perceived their office lighting to be of higher quality rated the office as more attractive, reported a more pleasant mood, and showed greater feelings of health and well-being at the end of the day. Other studies (Veitch et al., 2007) have demonstrated that satisfaction with lighting contributes to greater environmental satisfaction which in turn leads to greater job satisfaction, a factor that influences organizational commitment (Carlopio, 1996; Wells, 2000). Long-term field studies are required to validate this model and to quantify the strength of the links established.

17.5 PROBLEMS WITH INCREASED PRESSURE

The increased pressure for reduced electricity consumption by lighting and less light pollution can be partially assuaged by developments in technology. More efficient light sources, better luminaires that direct light only to where it is required, and control systems that ensure the right amount of light is provided only when it is needed are part of the answer. However, given that the most effective approach to reducing electricity consumption by lighting is to reduce the recommended illuminances, there is definitely a need to identify how far illuminances can be reduced without complaint in a wide range of situations. Likewise, switching off lighting late at night to reduce light pollution may have adverse effects on safety, security, and business. In other words, both pressures need to be balanced against the consequences of such actions. To make this balance more concrete, it is useful to consider an example. In the United Kingdom, local authorities have taken to switching off road lighting between about midnight and 5 a.m. Admittedly, they are doing this primarily to save money but exactly what the consequences are going to be for road safety will only be discovered in a few years time. The consequences of any proposed actions to reduce electricity consumption by lighting and light pollution is an area deserving of study.

Another way to meet the demands for reduced electricity consumption by lighting is to refine the spectral weighting of light so that the spectral power distributions of light sources can be better matched to the application. Rea (2013) has championed this approach by suggesting a number of alternative spectral weighting functions to be used instead of the CIE standard photopic observer (V_λ). The V_λ function is suitable for quantifying the effect of light on the ability to see detail with the fovea in photopic conditions, but for off-axis detection in mesopic conditions or for predicting brightness perception or for evaluating the stimulus to the circadian timing system, it is misleading. By adopting different spectral weighting functions for different applications, it would be possible to increase the efficiency of lighting for those applications. However, if this approach is to be successful, it will require lighting researchers to reach a consensus on suitable spectral weighting functions for specific common applications and for the lighting industry to be willing to adjust to a new flexibility in how light is defined. Whether either of these requirements will be met remains to be seen.

17.6 RESEARCH APPROACHES

Given that research is required in a number of areas, it is now necessary to consider how such research should be conducted. Before dealing with specific approaches, it is worth pointing out three general aspects of relevance. The first is the need to put people first and lighting second. In the past, experiments have been undertaken where the independent variables have been such basic features of lighting as illuminance, different glare conditions, and colour properties of light sources. These variables have been chosen because they are important to the lighting equipment manufacturer or are used in lighting design calculations, and not because they necessarily reflect factors that are important to the people using the lighting. It may be of some relevance to the designer's immediate problem if, for example, the CRI of a light source can be shown to relate to the ease with which different hues can be discriminated; but it is not getting at the root of the problem. To do this, it is necessary to gain an understanding of how people discriminate between colours. Once this has been achieved, a suitable measure of the relevant light source properties can be developed. To achieve a more fundamental understanding of how people respond to lighting, it is necessary to put people first and the lighting conditions second. Further, the people considered have to be representative of actual users in all their diversity.

Another general requirement for effective research is to develop more conceptual models. Concepts are important for research. They form the unstated assumptions within which research is conceived. Concepts that are explicitly stated become theories and theories give rise to hypotheses that can be tested by experimentation. About the only area of lighting research which can be said to have followed this route through concept/theory/hypothesis/experimentation is the study of visibility. This is for two reasons: first, because visibility is an obvious and immediate impact of lighting and has been studied for many years, and second, because visibility is a unique effect of lighting. Other areas of interest to lighting research, such as discomfort, impression, mood, and behaviour, are influenced by many factors in addition to lighting. In this situation, the need is for more conceptual models that span the effects of many different environmental and personal factors.

Finally, it is important to appreciate context. Quite correctly, a lot of past lighting research has been concerned with establishing general rules for providing lighting that allows work to be done quickly and easily, without discomfort. These general rules can now be said to be established. What deserves attention in the future is the extent to which these general rules need to be modified for different contexts, that is, for different applications and different groups of people. The point is which lighting conditions are most suitable depends on context. Until the importance of context is acknowledged, there is little likelihood of achieving a finer understanding of the effect of lighting in all its complexity.

Although putting people first, developing conceptual frameworks and an awareness of the importance of context is necessary for future research to be fruitful;

alone, they are not sufficient. For fruitful research to occur, the problems to be investigated have to be approached in the right way. In the broadest sense, this means considering the direction in which research should aim to move. For the study of the effects of light operating through the visual system, there is plenty of knowledge on which to base very general rules but little that is applicable to specific tasks. Hence, the need in this field of study is for a move from the general to the specific. For the study of the effects of light operating through the non-image-forming system, knowledge of how the circadian timing system works is growing rapidly. Unfortunately, the understanding of how changes in the status of the circadian timing system impact everyday activities is sparse. For this field of study, the present need is to move from the laboratory to the field. As for the study of the effect of lighting on mood, impression, and behaviour, the direction of movement here should be from the specific to the general. At present, there are some studies done in realistic conditions that have indicated how to create an impression with light. But these results only apply to the specific contexts in which they were obtained. What is needed in the future is for many more different contexts to be examined. If some consistency was then revealed, general rules about using lighting to create impression and direct behaviour could be formulated.

The direction of any research is only one aspect of the approach adopted. Another aspect is the techniques used to study the problem. There are several different approaches that can be used to obtain information about the effect of lighting conditions. They can be summarized as follows:

Epidemiological approach: This approach is used to determine if two variables are correlated, for example, if smoking cigarettes is related to the incidence of lung cancer. It is particularly useful as a method where there are many intervening factors that cannot be controlled and/or the effect does not occur until long after exposure to the stimulus. The overwhelming drawback of this approach is that it can only reveal whether two variables are correlated, not whether they are causally related. This means such studies are useful for determining if a relationship is worthy of further study, although such study should be undertaken only when a major effect is identified (Taubes, 1995). In fact, most epidemiological studies showing a statistically significant effect are the start of a race to determine the reason why the relationship occurred. For example, the finding that women working at night have a much higher incidence of breast cancer than those working by day (Hansen, 2001; Schernhammer et al., 2001) started a detailed search for the mechanism involved. It is only when the cause for the relationship is discovered that the specificity of the relationship becomes apparent. Given that a simple relationship has been found by epidemiology, the next step is usually to test it by selecting groups with different levels of exposure to the assumed important variable. If the outcome frequency increases with increasing levels of exposure, consistency is evident. Practically, the main drawback of the epidemiological approach is that it requires extensive databases of all the relevant information, databases that often do not exist or, when they do, have been created by accessing distant, unreliable memories.

Ecological approach: This approach is simply that of observation followed by interpretation, although it is sometimes possible to perturb the process by introducing a change in conditions. The study of Areni and Kim (1994) on the behaviour of people in a wine store under 'bright' and 'soft' lighting is an example of this approach. This approach is most suitable where the context in which the study takes place is important and removing the activity from the context would destroy the phenomenon being studied. The main disadvantage of this approach is that it cannot provide an explanation of why effects occur. Explanations that are given when using this approach are *post hoc* rationalizations. However, for some studies, such as the effect of lighting input conditions on behaviour, there is little alternative, because this approach provides the minimum interference with the natural condition. The ecological approach is useful for identifying lighting as an important variable but it can contribute little to understanding why this should be so.

Stimulus/response approach: This is the approach conventionally used in human factors research, vision research, psychophysics and environmental psychology. In its simplest form, a stimulus is administered to the person under controlled conditions and a response is measured. Experiments based on this approach require decisions about three classes of variables: independent, dependent and intervening variables. Independent variables define the conditions being examined by the experiment. Dependent variables are the output measures used to quantify the response to the independent variables. Intervening variables are all those factors that may influence the relationship between the independent and dependent variables. There are two types of intervening variables: those that need to be controlled and those that need to be measured in order to identify the reason for any change in the dependent variables. Experimental design procedures allow for several independent variables and the interactions between them to be examined in one experiment. Provided care is taken with the selection, measurement and control of independent, dependent and intervening variables and provided the statistical analysis of the collected data is thorough and appropriate, the stimulus/response approach can prove cause and effect. This is a great advantage over the epidemiological and ecological approaches. However, the stimulus/response approach does have one drawback, namely, that rigorous control of the intervening variables may destroy or modify the phenomenon being examined.

It would be a mistake to think these approaches are always mutually exclusive. Rather, different approaches are appropriate for answering different questions. It is very rare for a single experiment to provide a conclusive answer to a question. Usually, multiple experiments are required, with the results from different approaches providing mutual support. This ideal is called converging operations and is much like making a case for presentation in court. In the legal situation, the prosecutor has to prove that a crime occurred and that the accused had the means and the motive to carry out the crime. In scientific research, the researcher has to prove that lighting was responsible for the measured effect. To do that, the researcher has to prove that a change in response occurred and provide a proven mechanism through which lighting might act to produce that response.

As an aid in planning effective research, Wyon (1996) has introduced the idea of a linked mechanisms map. A linked mechanisms map sets out all the pathways between the independent variables and the dependent variables in a specific experiment. It is only when all the steps along one or more pathways have been proven that the effect of the independent variable on the dependent variable can be said to be established. Veitch et al. (2008) have used a linked mechanisms approach to demonstrate a statistically significant path between lighting conditions and feelings of health and well-being. Linked mechanisms maps provide a rational basis for answering the question 'Why do you expect your independent variable to affect your dependent variable?' This question needs to be addressed at the planning stage of an investigation. Without a rational answer to this question, any research project is reduced to a 'fishing expedition'.

The stimulus/response method is particularly attractive when both input and output variables can be objectively measured and the impacts of the input variables on the output variable are evident instantaneously. Where these conditions do not apply greater uncertainty is inevitable. Examples of questions where variables cannot be objectively measured are 'Will this lighting installation cause discomfort?' and 'Can I change the mood of people by changing the lighting?' The problem is how to measure discomfort and mood. There are two options. The most widely used is to have the subject complete a questionnaire designed to measure the attribute of interest. This can seem deceptively easy but questionnaire design and verification that the questionnaire is measuring what it is supposed to measure are fraught with difficulty (Rea, 1982; Tiller, 1990; Tiller and Rea, 1992). Part of the problem is that people taking part in an experiment will almost always give an answer to a question, even if it makes no sense to them. This problem can be overcome by careful testing of the questionnaire to demonstrate its validity and consistency (e.g. Mehrabian and Russell, 1974; Eklund and Boyce, 1996). The other option is a system of converging operations based on a series of operational definitions. Operational definitions can take several different forms but the most common are behavioural or physiological. For example, if the phenomenon is a feeling of discomfort caused by glare, discomfort could be operationally defined either as the electrical strength of the contraction of the muscles around the eyes (Berman et al., 1994a) or as the number of times the subjects shield their eyes with their hands or the extent to which the eyes are seen to be watering. If it can be shown that either physiology or behaviour increases in frequency and/or magnitude for the same conditions that produce an increase in ratings of discomfort in the questionnaire, then greater confidence can be placed on any conclusions reached.

One problem associated with the use of operational definitions is that too often the specific measure is soon replaced in the text describing the research by a generic term, for example, the number of times the eyes are shielded is replaced by the generic term discomfort. Of course, this is a matter of writing style rather than an inherent limitation of operational definitions, but such a practice can lead to confusion when different papers using different operational definitions of discomfort are compared. Indeed, it produces an echo of the words of Humpty Dumpty in *Through the Looking Glass* 'When I use a word it means just what I choose it to mean – neither more nor less'. Where operational definitions of a phenomenon are used, it is essential to know what the definition is because different operational definitions will have different sensitivities to the phenomenon. It is important to appreciate that the use of questionnaires or operational definitions does not exclude the application of the classic stimulus/response method. Indeed, its use is desirable to offset the inherent ambiguity and variability in such concepts as discomfort and mood.

This discussion of the possible approaches to investigating the roles of lighting on human health, performance, comfort, behaviour and mood is by no means complete. More extensive advice on experimental design can be found in the literature (Sheskin, 2004; Kirk, 2012). Designing experiments is an art because it requires choices to be made about the number and level of independent and dependent variables, control of intervening variables, number and type of subjects, methods of measuring the relevant variables, methods of statistical analysis and possible conclusions, all balanced against the resources of time and money available. For such choices to be successful, it is essential that the researcher is clear about the objectives of the proposed experiment, about what it can do and what it cannot. Good research does not necessarily require immense resources. What it does require is careful thought, so much so that it is sometimes claimed that a prerequisite for good research is the identification of a good question.

17.7 NEW TOOLS

Identifying a good question may be the foundation of good research, but sometimes it is not enough to get the research done. This is because of the difficulties inherent in answering the question. One area in which this has been a problem is examining discomfort glare from windows. The reason this has been a problem is that the luminance of the window can be very non-uniform and can change rapidly. As long as the luminances of the window had to be measured one point at a time, it was difficult to accurately quantify the independent variable. Fortunately, a new tool is now available that overcomes this problem. This is high dynamic range imaging (HDRi) (Inanici, 2006). This uses a high-resolution digital camera to capture a number of images of the scene at different exposure settings. Each image captures a limited range of luminances. By later combining these images into one continuous scale, it is possible to obtain a single image of the scene. The advantages of HDRi are that it enables a high-resolution image of a scene with a wide luminance range to be collected in a short time. This makes it suitable for measuring the luminances in any experiment where the scene is complex, covers a large range or may change rapidly. HDRi has been used in studies of discomfort glare from windows (Suk and Schiler, 2013) and from non-uniform luminaires (Cai and Chung, 2013).

Another area where research has been difficult is examining the role of light distribution on the perception of spaces, both indoors and outdoors. This difficulty is purely practical. To vary light distribution systematically as part of an experimental design requires frequent changes of luminaires, something that is always possible but often difficult to arrange in practice. Fortunately, developments in computer simulation have now made it possible to produce realistic images of lit scenes. Such scenes can be used as stimuli in their own right. This is the approach taken by de Kort et al. (2003) who examined the effect of plants on peoples' assessments of a real and simulated environment and found some similarities in the evaluations, as well as by Villa and Labayrade (2013) who have set out the conditions necessary for assessing luminous environments online. Simulated, photometrically accurate images can also be used to derive relevant photometric quantities such as luminance contrasts and visual size; Rea et al. (2010b) have used this approach to examine the effect of different forms of road lighting on driver's visual performance at junctions. The ability to create virtual, photometrically accurate images of scenes and to use them in experiments conducted over the internet is an exciting prospect. It means lighting stimuli can be created that do not exist in practice. Such a tool would be useful during product development or for testing new design methods as well as carrying out conventional experiments on such important aspects of lighting design as illuminance uniformity and the perception of safety.

Another area in which new tools have become available is field measurements of light exposure. Most of the research exploring the impact of light on the circadian timing system has been done in laboratories under very tightly controlled conditions. This research has been successful in demonstrating some of the ways light exposure influences the operation of the non-image-forming system. Another branch of research has been using epidemiology to study the impact of night-shift work on human health, the concept being that exposure to light at night can have adverse effects on human health. To link these two strands of research, it is necessary to know the light exposure patterns of people in the real world. Devices to do this have been available for a number of years but increases in computer power and miniaturization have now made them small enough to be easily worn all day in positions where they accurately measure the irradiation received at the eye (Hubalek et al., 2006, 2010; Figueiro et al., 2013c). Such measurements can provide explanatory power when considering the results of epidemiological or ecological studies. They might also be used to identify populations at risk of circadian disruption.

These new tools offer new opportunities for researchers but they should not be used without thought. Just because something can now be measured conveniently does not mean that it should. One situation where this is apparent is the use of eye-tracking devices. Eye trackers have been available for many years, initially with a limited field of view but now sufficiently sophisticated that they can be used outdoors (Davoudian and Raynham, 2012). Eye trackers identify where people are looking but say nothing about whether or not the individual is paying attention to what they see. For that to be known, data on the information collected through vision would have to be recorded. Such observations imply that new tools are just that, tools. When applied correctly, they can be invaluable but their use should not be an end in itself.

17.8 EVALUATING RESEARCH

Anyone interested in understanding the meaning of piece of research needs to have the ability to evaluate the reality, strength and stability of any effects claimed. To do this requires consideration of a number of characteristics of the effect. The first characteristic is its statistical significance. This is necessary because much lighting research involves people, and people have different physiological capabilities and psychological dispositions. The result of these differences is usually a lot of 'noise' in the measurements. The presence of measurement 'noise' means that the question 'Is this effect real or is it due to chance?' is always a legitimate one. Answers to this question are given in terms of a probability that the effect could have occurred by chance, that is, its statistical significance. Conventionally, a 5% probability that the effect is due to chance is taken to mean that the effect is real, although there is still a 1 in 20 possibility that it is not. Of course, lower percentages of occurrence by chance give one more confidence in concluding that the effect is real, but setting a lower statistical significance criterion also means increasing the risk that you will conclude that an effect occurs by chance when in fact it is real. Where the weasel words 'the results were not statistically significant but the means show a trend in the expected direction' occur, judgment on the reality of the effect should be suspended until further data have been gathered.

Given that an effect has been shown to be statistically significant, it is then necessary to examine its effect size. Effect size is a quantity that characterizes how much of the uncertainty in the output variable is explained by changes in the input variable. What this means is evident from a comparison of Figures 10.21 and 10.27. Figure 10.21 shows the luminance necessary for red vehicle tail lights, reflective discs and pedestrian dummies to be just visible (output variable), plotted against the visual area of these objects (input variable). Also shown is the best-fitting regression curve through the data. Figure 10.27 shows the ratio of accidents found to occur on different roads by night and day (output variable), plotted against the average road surface luminance provided by the road lighting at night (input variable). Again, the best-fitting regression curve through the data is shown. In Figure 10.21, the data points all lie close to the curve so visual size explains a lot of the variability in the luminance required to make the object just visible, that is, it has a large effect size. In Figure 10.27, the data points are widely scattered on either side of the curve, so in this case, the average road surface luminance explains very little of the variability in night/day accident ratio, that is, it has a small effect size. The larger is the effect size, the more important is the input variable in determining the change in an output variable. Formally, the effect size is the percentage of variance in the output variable that is explained by the change in the input variable.

Different fields of study tend to treat different effect sizes as acceptable, because of the differences in the 'noise' associated with measurements. For the physical sciences, where very accurate measurements are possible and many of the input variables can be tightly controlled, only large effect sizes (>90%) are acceptable. For human factors, where people are involved so measurement is often less exact and many of the input variables are unknown or can only be loosely controlled, much lower effect sizes are acceptable. Cohen (1988) suggests three effect size minima as benchmarks in this field: large effect size = 25%, medium effect size = 9% and small effect size = 1%. Of course, these minima apply to single variables. It is quite common to examine the effect of multiple input variables on an output variable, either independently or in combination. In this situation, the effect size for all the input variables together may be large, even though the effect sizes for each variable separately are small. Input variables that explain a very small percentage of the variance in the output variable are unstable and not to be trusted. In consequence, the predicted magnitude and direction of an effect derived from a regression equation or a set of means should not be believed unless the effect size is appropriate for the field of study.

Having determined that the effect being considered is real and explains a worthwhile amount of the variance, it is then necessary to consider the magnitude and direction of the effect. The magnitude is a measure of the predicted impact an input variable will have on the output variable. The direction of the effect is whether increasing the input variable increases or decreases the value of the output variable. Quantifying the predicted magnitude and direction of the relationship between the input variable and the output variable is useful because it helps with the decision as to whether the relationship is of practical importance. Achieving statistical significance and having an acceptable effect size are not enough to guarantee practical significance.

Once an effect has been found to be real, of an appropriate effect size and of practical significance, it is necessary to consider its reliability. Reliability is shown by replication. An effect is said to have been replicated when it has been shown to occur repeatedly in the same conditions, preferably by independent investigators. Replication is essentially the saying 'once is an accident, twice is coincidence, thrice is deliberate' in action. In the words of one group of researchers, 'For any scientific study, regardless of the strength of the initial findings, replication is the acid test of validity' (Heschong-Mahone Group, 2003c).

Another factor to be considered is consistency. Science progresses by an aggregation of results and models that fit a wider and wider range of situations. This means that an effect that is consistent with previous work is more likely to be correct than one that is not, although there have certainly been examples in the history of science where this has not been true and new understanding has resulted. Indeed, Barber (1976) argues that an unthinking adherence to an existing body of knowledge can act as a set of blinkers on 'seeing' what the outcome of an experiment really means. A link to current understanding is frequently used in the design of experiments by ensuring that at least one of the input variables allows a well-established relationship to be tested. By anchoring the experiment to established knowledge and demonstrating the expected result, any extension into new areas has greater credibility.

Demonstrating that there is a statistically significant relationship between an input variable and an output variable tells us only that the two variables are related. A correlation tells us nothing about the cause of that relationship. A cause is some mechanism, physical, physiological or psychological, that links the input variable to the output variable. Identifying the cause of an effect is essential for an understanding of the phenomenon being studied, particularly the conditions under which the effect will break down. All statistically significant effects should be considered as correlations until a plausible cause has been identified. This is not to say that an effect without an identified cause is wrong or unimportant but rather that the nature of the relationship is imprecise. Even where a cause for an effect has been identified, it is worth asking if there are alternative explanations. Such alternatives can range from failings in the experimental design, for example, important variables left uncontrolled, or systematic practice and fatigue effects to other mechanisms than that proposed which would have the same effect on the output variable in the conditions of the experiment.

In addition to considering replication, consistency and cause, any thoughtful consideration of research will examine to what extent there is evidence of convergence. This is a matter of the number of different ways in which the effect can be demonstrated. The more ways in which the same effect can be demonstrated, the more robust is the relationship. For example, Boyce et al. (1997) examined the impact of different lighting conditions on people working night shift. The hypothesis was that exposing people to high light levels at night would suppress melatonin and thereby increase alertness which would improve task performance. Exposure to high light levels at night did show an improvement in performance for some complex cognitive tasks, but, in addition, higher light levels were shown to increase subjective alertness and core body temperature and to delay the time at which the people went to bed in the morning. This pattern of emotional, physiological and behavioural effects is mutually supportive of the hypothesis that exposure to bright light at night impacts human behaviour through the circadian timing system.

Having established that an effect is real, of a worthwhile size, practically significant, reliable and consistent, it is essential to consider how specific it is, for example, is this effect likely to occur with elderly people with degraded visual systems? The specificity of an effect is a matter of the range of conditions over which the effect occurs. An effect that occurs only under very specific conditions is of limited interest. An effect that holds over a wide range of conditions is of much greater value. Strictly, an effect is only true for the ranges of the input variables examined but to accept this without argument is an excuse for not thinking. After all, the whole purpose of research is to generate knowledge that can be used to predict the future. There is thus every reason to try to answer this question, using whatever knowledge or theory is available, the purpose being to identify the boundaries beyond which the effect is likely to fail. It is much easier to suggest where these boundaries might be if the cause for the relationship has been identified.

Finally, given that an effect is statistically significant and has a meaningful effect size, it is essential to ask where on the cycle of observation, hypothesis, experimentation and validation the research lies. Some studies are undertaken to test predictions based on theories while others are undertaken to test a hypothesis based on observation. A result that confirms the quantitative predictions of a theory can be taken as validation of the theory. Such validations are not new knowledge but are essential for science to progress. The existence of discrepancies between the predictions and the outcomes suggests that, at the very least, the theory needs to be modified or, at the very most, that it should be abandoned.

The benefits of such a process of evaluation are shown by a series of studies undertaken to examine the effect of the amount of daylight in a classroom and the rate of learning of the children in the class. There is no necessary relationship between these variables, and there are many factors other than lighting conditions that are known to influence the rate of learning, for example, children's socioeconomic status and teachers' classroom management (Wang et al., 1993). The first of these studies examined the impact of having daylight in classrooms on the performance of elementary school children on standardized tests for three school districts (Heschong-Mahone Group, 1999b; Heschong et al., 2002b). The school districts were in three different US states, each having different climates, different building types, different curriculums and different testing protocols. In total, the performances of about 8000 students were examined in each district. For two of the districts, Seattle, Washington, and Fort Collins, Colorado, a multiple linear regression analysis was undertaken of the relationship between end-of-year performances on maths and reading tests and multiple input variables. One of the input variables was a daylight code reflecting the combined effects of windows and skylights on daylight provision. These regression equations showed a statistically significant effect of daylight ($p < 0.01$), the students in classrooms with the most daylighting having a predicted 7%–13% higher test scores than those whose classrooms had the least daylighting. In the third district, Capistrano, California, multiple linear regression analyses were undertaken of the relationship between the difference in performance on standardized maths and reading test scores between autumn and spring and 50 input variables, one of which was the daylight code. The effect sizes for the complete regression equations were in the range 25%–26%. These regression equations also showed statistically significant effects of daylight ($p < 0.01$) although of very small effect size (<1%). As for magnitude and direction, the regression equations predicted that the students in classrooms with the most daylighting would progress 20% faster in maths and 26% faster in reading than those whose classrooms had the least amount of daylight.

The important educational and societal implications of these predictions generated a lot of interest despite the fact that the effect sizes associated with the daylight code were very small. An attempt at replication was made in a similar but more sophisticated study undertaken in the Fresno, California (Heschong-Mahone Group, 2003c). In total, the changes in performance on standardized reading and maths tests over the school year were collected for approximately 8500 elementary students. Further, data on 150 input variables were collected either from the school district's databases or during visits to the 500 classrooms occupied by the classes participating. These 150 variables were grouped into those concerning the school site, student characteristics, teacher characteristics, school demographics, daylight characteristics, classroom characteristics, indoor air quality, noise and electric lighting. Ten student characteristics and five teacher characteristics showed consistent statistically significant effects related to progress in mathematics and reading at the rather liberal probability of occurrence by chance of 10%. The 10 student variables were the grade level; the percentage attendance; whether the student was qualified or enrolled in a gifted and talented education program; whether the student was a special education student; the level of English language development; whether the student was the recipient of a free lunch; whether the student was the recipient of a reduced cost lunch; whether the student was living in a nonstandard situation, for example, foster care; the student's gender and the student's ethnicity. The five teacher variables were the teacher's annual salary, the number of years the teacher had been employed in the Fresno Unified School District, whether the teacher was a mentor teacher, whether the teacher was a pre-tenure teacher and whether the teacher was responsible for more than one grade level in the same classroom. With this number of input variables, any effect of daylight is likely to be highly diluted.

Having established these base variables, the next step was to replicate the previous study by adding six variables similar to those that had been found to be statistically significant in the Capistrano study (operable windows, portable classroom, open classroom, classroom size, school population and school age) together with the daylight code variable that quantified the daylight provision. Despite the fact that the Capistrano study had predicted a major impact of daylight on progress in maths and reading, the daylight code did not have a statistically significant effect on progress in maths and reading in Fresno. In other words, the replication failed. This led to a series of alternative groupings of the input variables in an attempt to clarify the role of daylight but with little success. Some statistically significant effects of daylight were found but these all had effect sizes of less than 1%. The problem with variables that explain so little variance is that they are very unstable. This is shown by the fact that even when they are statistically significant, they can change the direction of their effect. For example, the daylight code explained 0.3% of the variance in the Capistrano maths model and had a positive effect, that is, the more daylight, the greater the progress. In the Fresno maths model, the daylight code explains less than 0.1% of the variance and has a negative effect, that is, the more daylight, the less the progress. In the Fresno reading model, the daylight code explained 0.1% of the variance and had a negative effect, that is, the less the daylight, the greater the progress in reading.

This instability opens the question of cause. For both the maths and reading models, it was found that both a high daylight code and a low daylight code were most beneficial for progress. Specifically, classrooms with good uniform daylight, a nice view and controls on the window so that glare was avoided were good for progress, as were classrooms with very little daylight and good control on what windows there were. The worst classrooms for progress were classrooms with some daylight, without a nice view and with windows oriented so as to experience glare from the sun and without any control on the windows. There was also a relationship between the extent of glazing and the classroom acoustics. Classrooms with extensive windows had longer reverberation times, tended to receive more noise from outside because the windows were sometimes open and, because of the structure of the school, tended to have some in-class tutoring going on in the classroom at the same time as the lesson. The classrooms with little daylight were arranged so that any special tutoring could take place outside the classroom.

What this discussion reveals is the need to evaluate all the characteristics of a proposed effect before accepting its validity. Achieving statistical significance is necessary but not sufficient to establish proof. It is also essential to consider the effect size, whether or not it has been replicated, what might be the cause and how specific it is. Based on statistical significance alone, the aforementioned study could be taken to mean that providing daylight in classrooms is a magic bullet for enhancing student progress everywhere. A more complete evaluation shows this is not the case. Rather, whether daylight has a positive or negative effect on student progress depends on how it is delivered, that is, the impact of daylight is very specific. The implication is that daylighting that provides an even distribution of daylight, an extensive view, and limits glare and thermal heat gain is likely to make a positive contribution to student progress. If having more windows increases the noise level in the classroom and hence makes it more difficult to hear the teacher, or if glare from the sun makes it more difficult to see the teacher's working, or if what is happening outside is distracting and visible through the window, then more daylight provided through the windows is likely to slow students' progress.

The main reason for reviewing the factors to be considered when evaluating research in such detail is that, in the last decade, the questions that lighting research seeks to address have become much more diverse and complex. A consequence of the increased diversity and complexity of questions addressed has been an increased diversity and complexity in the methods used. This demands that the means used to evaluate lighting research be upgraded. It is hoped that this discussion represents a start in this process.

17.9 SUMMARY

This chapter is addressed to those who are, or will be, concerned with lighting research. It begins by discussing the problems facing lighting today and what lighting research might contribute to their solution. Broadly, these problems are associated with new technology, new knowledge and growing concerns about the economic and environmental consequences of lighting. Each of these problem areas requires some input from lighting research.

What that research might be can take several different forms ranging from epidemiology through ecology to classic stimulus/response methods. Epidemiology is most useful when there are many intervening factors that cannot be controlled and/or the effect does not occur until long after exposure to the stimulus. The overwhelming drawback of this approach is that it can only reveal whether two variables are correlated, not whether they are causally related. The ecological approach is simply that of observation followed by interpretation. This approach is most suitable where the context in which the study takes place is important and removing the activity from the context would destroy the phenomenon being studied. Again, the main disadvantage of this approach is that it cannot provide an explanation of why effects occur. Explanations that are given when using this approach are *post hoc* rationalizations. By far the most common approach used in lighting research is the stimulus/response method. Provided care is taken with the experimental design and the statistical analysis of the collected data is thorough and appropriate, the stimulus/response approach can prove cause and effect. The one drawback of the stimulus/response approach is that rigorous control of the intervening variables may destroy or modify the phenomenon being examined.

Designing experiments is an art because it requires choices to be made about the number and level of independent and dependent variables, control of intervening variables, number and type of subjects, methods of measuring the relevant variables, methods of statistical analysis and possible conclusions, all balanced against the resources of time and money available. For such choices to be successful, it is essential that the researcher is clear about the objectives of the proposed experiment. Fortunately, good research does not necessarily require immense resources. What it does require is careful thought, so much so that it is sometimes claimed that the foundation of all good research is the identification of a good question.

Identifying a good question may be the foundation of good research, but sometimes it is not enough to get the research done. This is because of the difficulties inherent in answering the question. These difficulties include stimuli that are complex and that change rapidly, for example, the luminance distribution of a window; logistical problems associated with providing the necessary conditions, for example, frequent changes of luminaires; and the difficulty of measuring real-world conditions, for example, measuring the exposure to light over several days. Fortunately, developments in technology have delivered new tools to address all these problems.

HDRi provides rapid measurement of complex luminance fields. Photometrically accurate computer simulations can be used to provide virtual representations of real scenes. Measurement devices for recording light exposure that can be worn during normal daily life are now available.

Designing experiments to address problems is inherent in any lighting researcher's job description but so is evaluating their own research and that of others. To do this requires that attention should be paid to statistical significance to ensure the effect is real and not due to chance, to effect size to quantify how much of the uncertainty in the output variable is explained by the input variable and to the magnitude and direction of the effect to decide whether or not the effect is of practical significance.

Once an effect has been found to be real, of an appropriate effect size and of practical significance, it is necessary to consider its reliability and consistency. Reliability is shown by replication, and consistency is evident when the effect is consistent with previous work. An experimental result that is statistically significant, is of reasonable effect size, is of practical significance, has been replicated and is consistent with other work is satisfactory. It is even more satisfactory if there is a plausible cause and the boundaries beyond which it might be expected to fail are clear. Such a systematic evaluation of research is necessary because over the last decade, the questions that lighting research seeks to answer have become more diverse and complex. It is only by careful experimental design and the systematic evaluation of the outcomes that progress in understanding all the contributions of lighting to the quality of life of humans will be made.

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