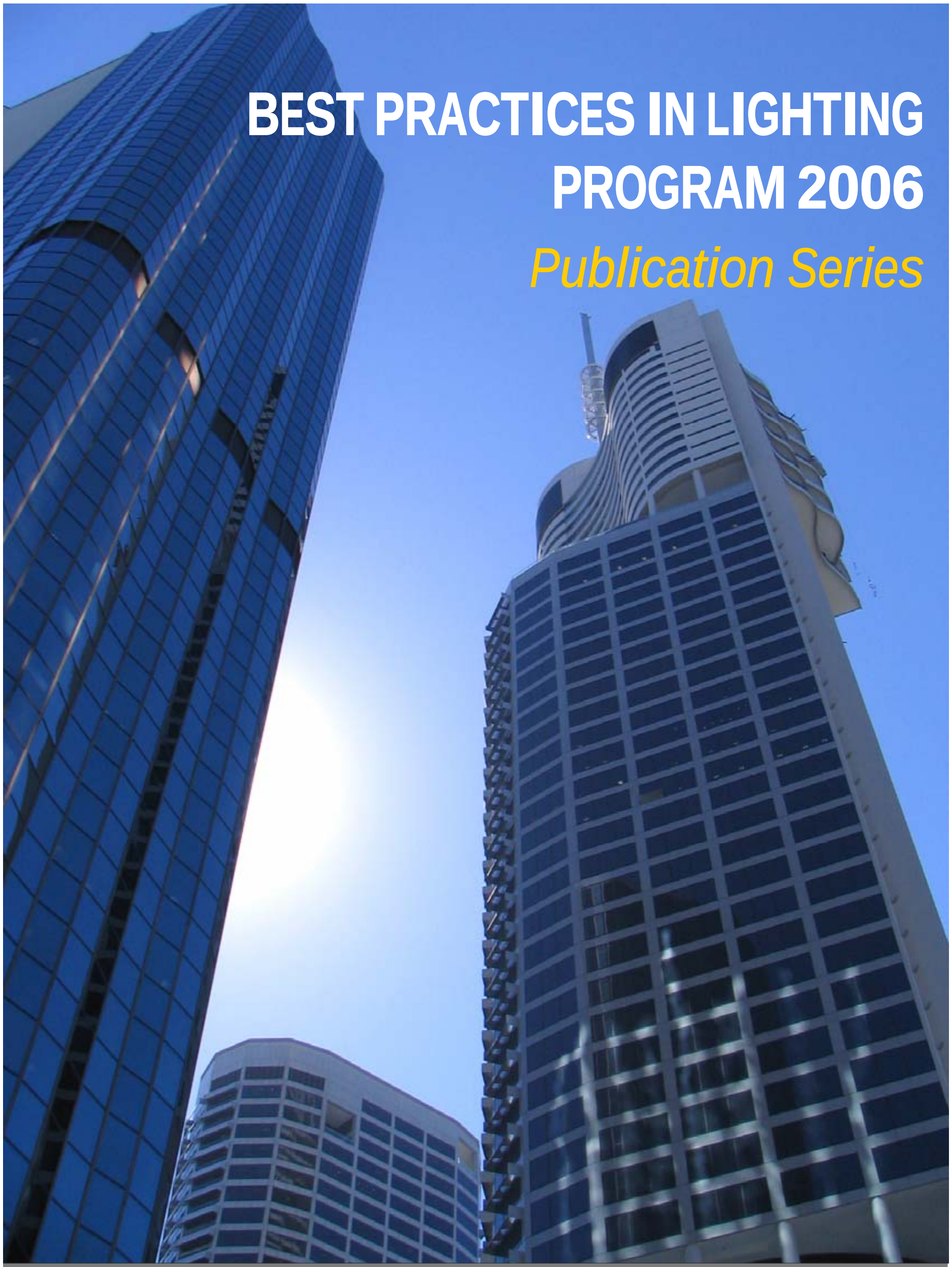

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11. Developments in the Human Factors of Lighting

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DEVELOPMENTS IN THE HUMAN FACTORS OF LIGHTING

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Abstract

Recent developments in human factors research have lead to new understanding in a number of areas, understanding that has the potential to change lighting practice. These developments have been in the areas of lighting quality, scotopically enhanced lighting, illuminance choices, mesopic photometry and light and health. This paper summarizes developments in each of these areas and examines their implications for lighting practice.

1. Introduction

Human factors in lighting is the study of the interaction of people and light. Human factors is important because it provides the basis for lighting practice. How much light should be provided, what light spectrum is chosen and what light distribution is used in any application are all influenced by how people respond in terms of perception, performance, behaviour and health. Recent developments in human factors research have lead to new understanding in a number of areas, understanding that has the potential to change lighting practice. These developments have been in the areas of lighting quality, scotopically enhanced lighting, illuminance choices, mesopic photometry and light and health. This paper summarizes developments in each of these areas and examines their implications for lighting practice.

2. Developments in lighting quality

2.1 Classifying lighting quality

In order to discuss lighting quality it is necessary to have a classification system. My belief is that the bulk of lighting practice 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 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.

Bad lighting tends to be produced by ignoring authoritative guidance, by an excessive concentration on one lighting criterion at the expense of others and by a belief that energy efficient lighting is, by definition, good lighting. Bad lighting is the province of the ignorant.

Indifferent lighting is produced by the application of authoritative guidance without thought, particularly quantitative rather than qualitative guidance. Indifferent lighting is the province of the computer.

Good lighting is produced by the thoughtful application of authoritative guidance, by matching the lighting to the architecture and by sensitivity to time and place. 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.

On this scale, much of what constitutes current lighting practice for functional spaces falls into the class of indifferent lighting. Why is this? The answer is that for functional spaces, such as offices, there is no obvious economic incentive to go beyond maximizing visual performance and minimizing visual discomfort. To provide an economic incentive for lighting the space as well as lighting the task in functional spaces, it is necessary to demonstrate that lighting the space changes visual performance in some way.

2.2 The impact of lighting the space

Over the last few years a number of attempts have been made to quantify the impact of lighting the space by examining visual task performance done at constant task visibility but with different light distributions. Eklund et al (2000) had temporary office workers work for eight hours doing a data-entry task in a 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 for very uniform indirect lighting to very concentrated overhead lighting. There was no difference in performance of the task under the three lighting installations. 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 four hours, 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.

Finally, Boyce et al (2006) carried out two field simulation studies in which temporary office workers worked for a day in a multi-person office lit by one of four different lighting installations representative of modern North American practice. The work undertaken consisted of tasks dominated by their visual, cognitive and judgmental components. Interestingly, the participants discriminated between the lighting systems in terms of comfort but showed no effects of light installation on task performance although the expected changes in performance with task visibility, practice and fatigue were evident.

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. 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) where selected to cover the extremes of current lighting practice. It might also be important that the tasks done 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.

2.3 Implications for lighting practice

These attempts to demonstrate an economic incentive for good quality lighting in functional spaces lead to one clear conclusion. This is that, while lighting conditions that alter task visibility can be relied upon to change visual task performance, lighting distributions that do not affect task visibility or cause visual discomfort may not. They may, because light distributions can also affect the mood of the office worker, or they may alter the "message" sent by the lighting and this "message" may in turn alter behaviour. 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, but what form should it take? The studies described above were all done in a manner consistent with an experiment. Experiments are good for measuring what people can do but not so good for measuring what people would choose to do in a real situation because an experiment has its own context. This suggests that if we want to study the effects of lighting operating through mood we had better do it in realistic situations over prolonged periods, using people doing real work. In other words, we have to move from laboratory studies that treat people as machines, to a form of ecology where people’s behaviour in their natural environment is observed. Until this approach has been tried, knowledge of the impact of lighting the space for task performance will be incomplete but, currently, the obvious conclusion is that the lighting of functional spaces should be directed simply to providing good visibility without discomfort.

3. Developments in scotopically enhanced lighting

3.1 Scotopically enhanced lighting and visual acuity

Scotopically enhanced lighting is lighting in which the light source has a spectral power distribution matched to stimulate the rod photoreceptors but is used in photopic conditions. Interest in scotopically enhanced lighting was initiated when Berman et al. (1993) showed that light spectrum can influence performance of an achromatic task, specifically the accuracy with which the orientation of a Landolt ring can be identified. Figure 1 shows the proportion of correctly reported orientations for Landolt rings with a gap size subtending approximately 2 min arc at the subject's eye 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 4.3. The other light source was a mixture of red and pink fluorescent lamps, the combined effect having a scotopic / photopic ratio of 0.2. 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 did produce differences in task performance. The greenish-blue light source consistently has better task performance than the 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., 1994).

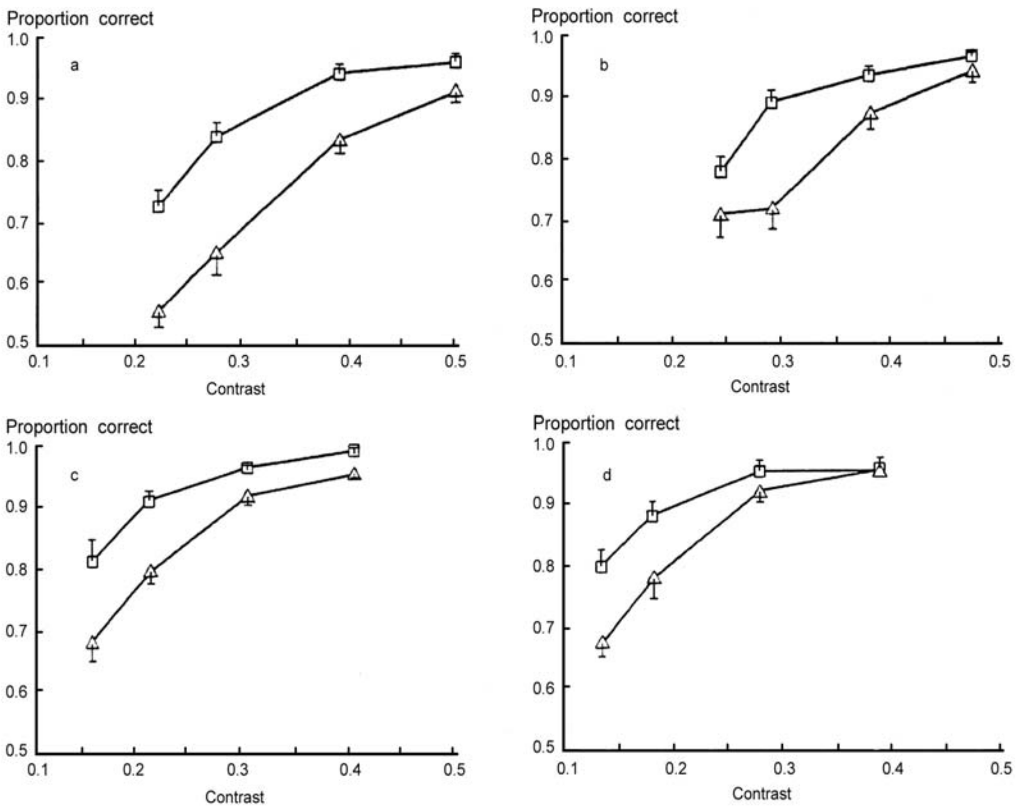

Figure 1 Means and associated standard errors of the proportion of Landolt ring orientations, presented for 200 ms on a spectrally neutral background, that were correctly identified, plotted against luminance contrast, for four different background luminances: a = 11.9, b = 27.7, C = 47.0, d = 73.4 cd/m^2. In all four diagrams, the upper curve (open square) is for the scotopically enriched greenish-blue illuminant (surround field scotopic luminances = 228 cd/m^2) and the lower curve (open triangle) is for the scotopically diminished, 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 et al., 1993)

More recently, Berman et al (2006) have shown that the use of high correlated colour temperature fluorescent lamps (6,500K) produced a statistically significant improvement in the visual acuity of 10 and 11 year old schoolchildren over that obtained at the same luminance provided by fluorescent lamps with a correlated colour temperature of 4,100K (Table 1)

Table 1. Mean minimum angle of resolution (min arc) of elementary schoolchildren for different light source correlated colour temperatures and task luminances (from Berman et al, 2006)

6,500K fluorescent lamps giving a task luminance of 85cd/m^2	4,100K fluorescent lamps giving a task luminance of 85cd/m^2	6,500K fluorescent lamps giving a task luminance of 43cd/m^2
0.81 min arc	0.92 min arc	0.88 min arc

3.2 An explanation

The proposed explanation for these findings of an effect of spectral power distribution on the performance of achromatic tasks rests on the role of pupil size. Specifically, pupil size in a large visual field is determined predominantly by the response of the rod photoreceptors, even in photopic conditions; the greater the response from the rods, the smaller the pupil area (Berman et al. 1992). For the light sources used in Berman et al (1993), the pupil area under the greenish-blue light source was 40 percent smaller than under the red-pink light source. For Berman et al (2006), measurements on four children showed that the pupil area under the 6,500K lamp was about 87 percent of that under the 4,100K lamp at the same luminance. 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 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 for tasks limited by resolution.

But this should not be taken to mean that the use of scotopically enhanced lighting would benefit the performance of all visual tasks. Boyce et al. (2003a) 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. Subjects performed a Landolt ring task for eight different gap sizes (1.5 to 14 min arc) at 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 (correlated colour temperatures of 3,000 K and 6,500 K). The speed and accuracy of performance of the task was 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 2)

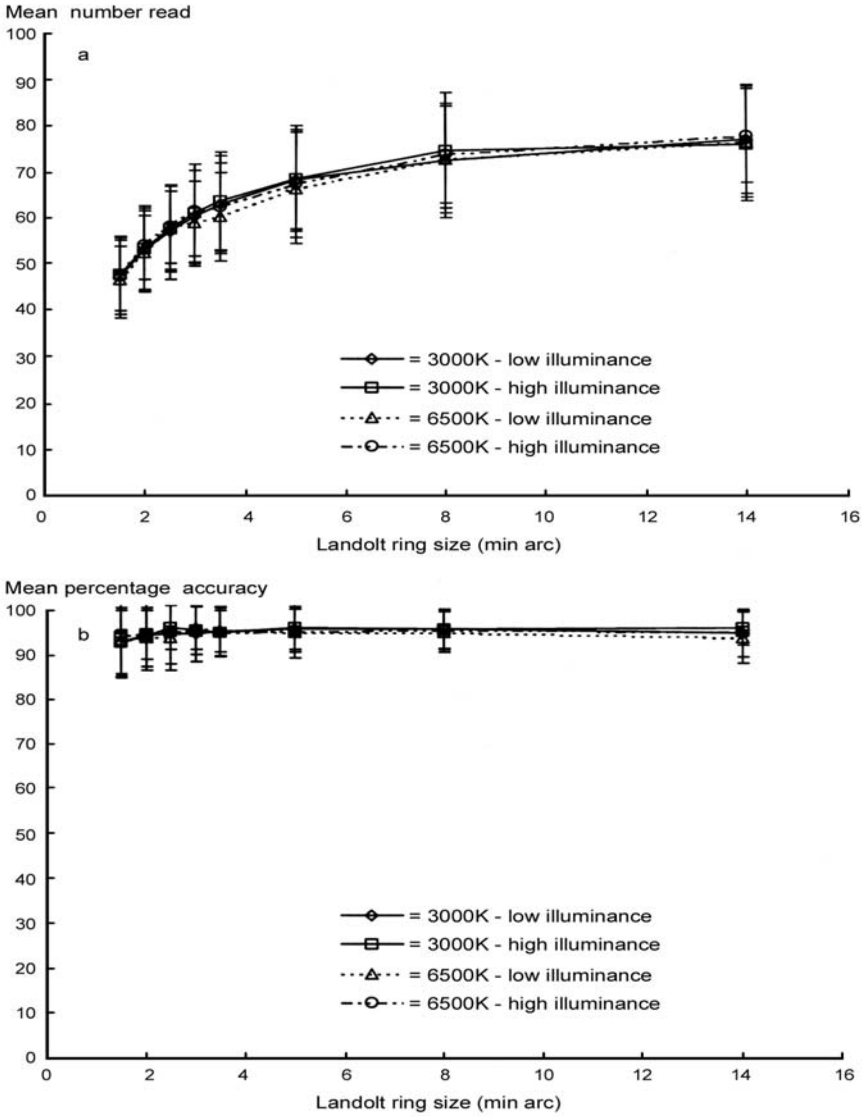

Figure 2 Means and standard deviations of the number of Landolt rings examined in twenty seconds and the proportion of Landolt rings of the specified orientation correctly identified, plotted against Landolt ring gap size, for two lamp types with correlated colour temperatures of 3,000 K and 6,500 K, at 344 and 500 lx (after Boyce et al., 2003a).

3.3 Implications for lighting practice

The implications of these studies for lighting practice are interesting. There can be little doubt that scotopically enhanced lighting can improve visual acuity and that the effect is comparable in size with what can be achieved by changing illuminance over a practically significant range. This implies that it would be possible to use lower illuminances with scotopically enhanced lighting and get the same visual acuity. Of course, visual acuity is not always important in lighting applications. For example, in a restaurant the appearance of the food, customers and decor is the more important the visual acuity and the use of a high correlated colour temperature lamp would be detrimental to appearance. But where visual acuity is a limiting factor, then scotopically enhanced lighting offers an opportunity to improve performance without increasing illuminance.

4. Developments in illuminance choices

4.1 The opportunity

Technology for lighting control has now advanced to such an extent that individual control of illuminances in multi-occupied spaces is a real possibility. The motivation behind such a provision is usually to save money and/or electrical energy but there are other benefits. A field simulation study of modern office lighting (Boyce et al, 2003b and 2006) showed that the percentage of office workers considering the lighting comfortable was only about 70 percent for a widely used fixed direct lighting installation but increased to 92 percent when direct / indirect lighting with individual control of the direct component was provided. Clearly, one-size-fits-all lighting does not.

In addition to increasing the number of people finding the lighting comfortable, measurements of the illuminances chosen can reveal what illuminances people prefer and hence offer an opportunity to re-examine lighting recommendations.

4.2 Data collection

The field simulation study (Boyce et al, 2003b and 2006) took place in a renovated office building furnished with cubicles, which is where the participants spent most of the day. Four different lighting installations were used in the study but only two allowed any choice. In the switching control installation, the lighting of the cubicle area was a suspended direct / indirect luminaire, and in addition each cubicle was fitted with a free-standing desk lamp with a translucent shade, which the occupant was free to operate by changing the setting of the switch at any time (Figure 3). In the dimming control installation, each cubicle had centred over it a suspended direct / indirect luminaire (Figure 3). The indirect component (1 lamp) operated at a fixed level, and the occupant could change the level of the direct component of the luminaire output at any time using an interface on the computer in the workstation. 33 temporary office workers experienced the switching control and 57 experienced the dimming control. Changes in cubicle lighting were automatically recorded throughout the day. These data can be used to answer a number of questions about individual control.

Figure 3. Cubicles used in the field simulation study (Boyce et al, 2003b and 2006) equipped with a switchable desk lamp (left) or a pendent luminaire that had a dimmable downward component. The difference in cubicle wall reflectance was balanced across both types of control.

4.3 How frequently do office workers use lighting controls?

The patterns of lighting control use are similar for the two forms of control. 33 percent of people never changed the switchable lighting and 11 percent never changed the dimmable lighting from the initial setting. Most who did change the lighting did so only once, usually at the start of the day. Other field studies in offices have observed the same pattern for the control of the whole lighting installation from a switch by the door (Hunt, 1979) for manual switching of individual luminaires through pull cords (Boyce, 1980) for overriding indirect luminaires that were automatically dimmed according to the level of daylight (Reinhart and Voss, 2003) and for pairs of recessed parabolic luminaires in offices in four different buildings, where each pair could be switched separately to different levels from a local signalling device (Moore et al, 2003) These findings from independent studies conducted at different times on different continents with different levels of technology imply a common, stable pattern of behaviour. This is to use the switching and dimming lighting controls to set the light level to what is expected for the day's work at the beginning of the day, and then to change it only when essential.

4.4 What illuminances do office workers choose?

The percentages of participants selecting different average desktop illuminances, in 100 lx bins, for the Switching Control and the Dimming Control conditions of the field simulation study are shown in Figure 4. The most noticeable features of Figure 4 are the wide spread of illuminances chosen by different participants and the very different distributions for the switching control and the dimming control. This latter difference is a matter of what lighting conditions it was possible to achieve. The switching control condition allowed only the addition of light to the ambient illumination provided by the indirect room lighting, whereas the dimming control allowed the ambient illumination of the cubicle itself to be reduced.

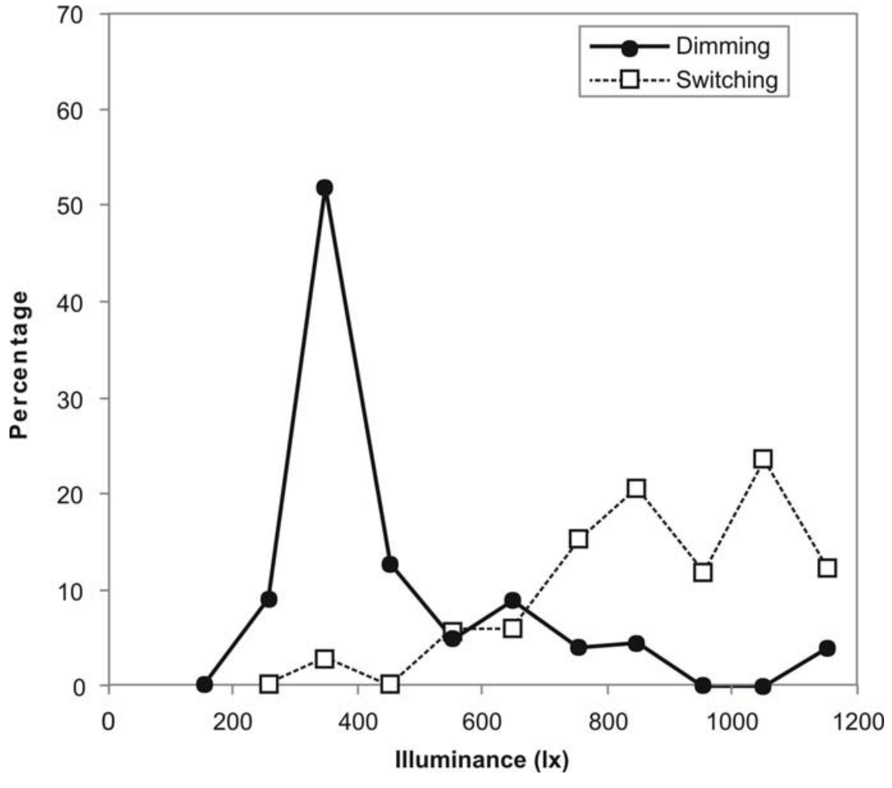

Figure 4. Percentage of participants choosing a mean desktop illuminance in 100 lx bins for the switching control and the dimming control conditions (from Boyce et al, 2003b).

The wide range of illuminance chosen by different people has been found before, in both field studies and laboratory studies (Love, 1998; Mannicia et al, 1999, Boyce et al, 2000; Veitch and Newsham, 2000 a and b; Newsham and Veitch, 2001; Moore et al, 2002). Figure 5 shows the frequency distribution of the average workstation illuminance chosen by 45 office workers in four different buildings in the UK that were monitored for several months (Moore et al. 2003). In these multi-occupied offices, occupants could switch individual luminaires either from their workstations or from a wall or column mounted switch. The average workstation illuminance experienced ranged from 91 lx to 770 lx. Figure 5 also shows the frequency distribution of the illuminances experienced at the end of the day in the field simulation study (Boyce et al, 2003b) where there was a range of illuminances from 252 lx to 1176 lx.

A Canadian laboratory study had two conditions that were somewhat similar to those of the field simulation study (Newsham et al, 2004). Those who had direct luminaires and an angle-arm desk lamp chose desktop illuminances across the range 188 lx to 1478 lx. Those with dimming control over a direct / indirect luminaire suspended over the centre of the workstation chose values over a range 116 lx to 1442 lx. Yet another laboratory study (Boyce et al, 2000) has shown large differences in the illuminance chosen by individuals to do the same tasks in a private office. The office was windowless and it was possible to dim the workstation illuminances over ranges of either 1240 lx to 12 lx or 680 lx to 7 lx. The median workstation illuminances chosen by the 18 participants for the same tasks range from 110 lx to 1230 lx for the larger control range, and from 80 lx to 630 lx for the smaller.

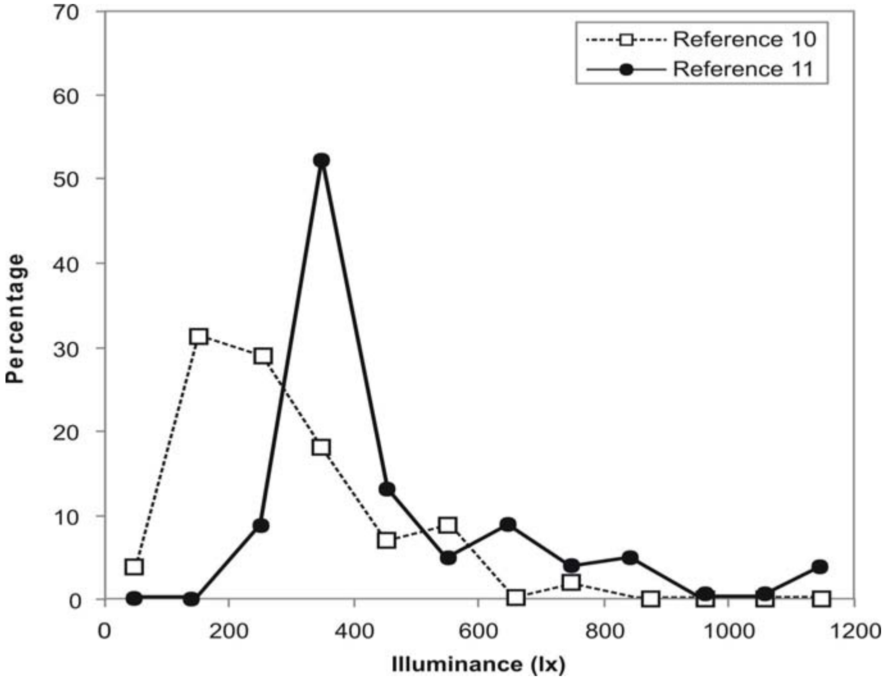

Figure 5. Percentage of office workers choosing to work at different illuminances, in a long-term field study (Moore et al, 2003 reference 10) and a short-term laboratory study (Boyce et al, 2003b, reference 11)

Taken together, these laboratory and field results support the view that although there is a stable pattern of when to use lighting, there are large differences between individuals in the illuminances they choose.

4.5 Are different illuminances chosen for different lighting designs?

Figure 4 makes evident that the switching control and the dimming control installations in the field simulation study – two different types of lighting control – provided very different illuminance distributions in the cubicles, allowed different minimum illuminances to be chosen, and led to very different frequency distributions of chosen illuminances. If the desire for the illuminances chosen using the dimming control had been absolute, most participants would have switched off the desk lamp in the switching control condition. Few chose to do so. Conversely, if the higher illuminances chosen when using the switching control had been absolute, then most people using the dimming control would have increased the illuminance much above the initial level. Few did so.

As for different types of electric lighting, when the lighting systems offer broadly similar luminous patterns in the working area, different lighting systems do not result in different mean illuminances being chosen. For example, Yoshida-Hunter (2003) examined the illuminances chosen in a private office lit by either direct or indirect electric lighting. The maximum illuminances available on the desk and on the monitor screen were very similar for both direct and indirect lighting. This was a laboratory study in which participants did the same tasks for an hour, by day and after dark. There was no statistically significant difference in mean illuminance settings for the two types of electric lighting.

However, when the lighting systems produce very different luminous patterns, different illuminances may be chosen. For example, Newsham et al (2004) found that when given the opportunity to provide extra light on the vertical partition surface of a cubicle using a custom-designed “partition washer”, participants used this luminaire to boost the vertical panel luminance.

4.6 What is the optimum illuminance for a fixed office lighting installation?

By now it should be clear that one fixed illuminance cannot satisfy everybody, in the same way that one air temperature will not make everybody thermally comfortable (McIntyre, 1980) Rather, there may be an optimal illuminance that maximizes the percentage of people who would consider the lighting comfortable. Newsham and Veitch (2001) examined this question using data from 47 temporary office workers who worked for a day in a windowless office at a series of screen-based tasks under lighting conditions chosen by another participant in the experiment. The range of desktop illuminance possible was 0 lx to 800 lx. At the end of the working day, the participant who had not been given a lighting choice at the start of the day was given the opportunity to adjust the lighting conditions to what he/she desired. Fitting a linear regression line to the resulting desired change in desktop illuminance plotted against the illuminance experienced during the day revealed that a desktop illuminance of 392 lx produced no desire for change; higher experienced illuminances produced a desire for lower illuminances, and vice versa. From these desired illuminances, it is possible to calculate the percentage of participants who would be within 100 lx of their desired illuminance at any given fixed illuminance (Figure 6). The result was a peak around 450 lx with only a slight drop between 350 lx and 550 lx, but no more than 45 percent of occupants were within 100 lx of their chosen illuminances no matter what fixed illuminance was chosen. Interestingly, participants who did not have a lighting choice at the start of the day and who experienced a desktop illuminance during the day that was within 100 lx of their preferred illuminances gave higher ratings of mood, lighting quality and overall environmental satisfaction than those who were further from their preferred illuminances. Figure 6 also shows the percentage of subjects in the field simulation study who were within 100 lx of their chosen illuminance for different fixed illuminances. It can be seen that the optimal illuminance is around 350 lx. At this illuminance 63 percent of subjects are within 100 lx of their preferred settings.

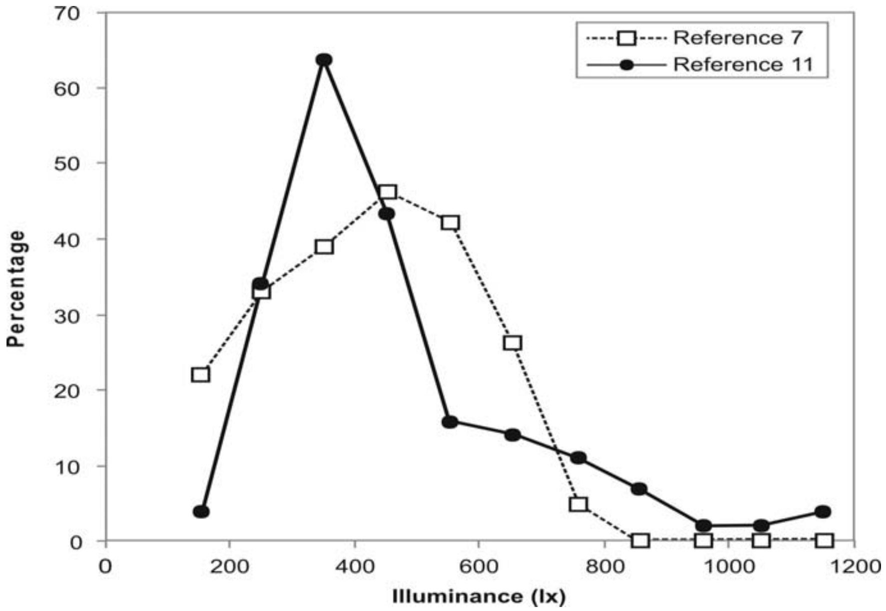

Figure 6. Percentage of participants within 100 lx of their selected illuminance for two studies (Newsham and Veitch, 2001 (reference 7) and Boyce et al, 2003b (reference 11)

Taken together, these results suggest that the optimal desktop illuminance for a fixed office lighting installation is about 400 lx. However, even at this illuminance a significant proportion of office workers is likely to be more than 100 lx from their preferred illuminances.

4.7 How do the chosen illuminances relate to recommendations?

The working plane illuminances recommended for offices in the UK are in the range 300 to 500 lx, the lower limit being recommended for mainly computer-based work and the upper limit for mainly paper-based work. Similarly, in North America working plane illuminances commonly range from 300 to 500 lx. For Australia and New Zealand, 320 lx is recommended for routine office tasks. These recommendations agree well with the range over which the largest percentage of people are within 100 lx of their individually desired illuminance (see Figure 6).

4.8 Implications for energy consumption

The implicit objective of much office lighting is to maximize office workers' satisfaction while minimizing energy consumption. Given this objective, there are two answers to this question, depending on the nature of the lighting. For a fixed lighting installation with little or no daylight contribution, the results in Figure 6 suggest that the maximum percentage of people who will be within 100 lx of their preferred illuminance, and hence who will be satisfied, occurs at a mean illuminance of about 400 lx. This implies that lighting practice that uses 500 lx as the target for maintained illuminance is excessive. By using 400 lx as a design criterion, a 20 percent decrease in energy consumption could be gained together with a likely increase in the percentage of office workers who are within 100 lx of their preferred illuminance.

For a lighting installation with an individual dimming capability, having the ability to vary the illuminance over a wide range produces an increase in the percentage of office workers who consider the lighting comfortable, from about 70 percent for installations consisting of regular arrays of either recessed parabolic or prismatic luminaires producing a fixed illuminance to 91 percent for the dimming control installation (Boyce et al, 2006) For a lighting installation with an individual dimming capability the maximum energy consumption and the first cost are largely determined by the highest illuminance provided. Figure 7 shows the percentage of office workers who would be unable to achieve their desired illuminance for a given maximum mean illuminance. It can be seen that in two studies

(Newsham and Veitch, 2001; Boyce et al, 2003) there is little benefit to be gained from having a maximum mean illuminance above 700 lx. Given this maximum mean illuminance, 90 to 99 percent of office workers should be able to achieve their chosen illuminance. Whether this would save energy relative to an installation with a fixed illuminance of 400 lx will depend on the lighting equipment, the chosen illuminances, and the degree to which individuals use their controls to switch off during periods of absence. Based on the data presented here it appears likely to be energy-neutral in spaces that lack daylight and that are occupied all of the time, because some people will choose illuminances lower than 400 lx and others higher. Where these conditions do not apply, individual dimming control offers the possibility of energy savings relative to a fixed lighting installation. This is because local control allows individuals to choose whether or not to switch on when they arrive at work or to switch off during short absences. Switching off, or leaving the lighting off, is unlikely when control is not local, but are observed for local control (Maniccia et al, 1999; Moore et al, 2002) In addition, where some of the workstations have daylight for at least some of the time there is a possibility of manual daylight harvesting if those individuals choose lower illuminances in the presence of daylight, as some evidence suggests they will (Moore et al, 2003)

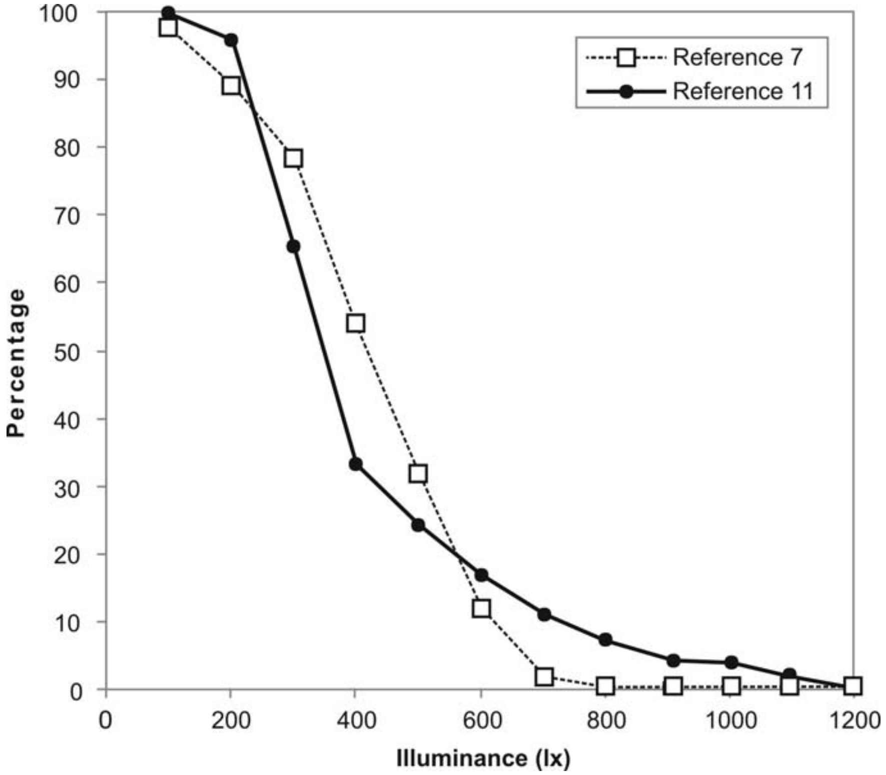

Figure 7. Percentage of participants who are unable to achieve their selected illuminance by dimming plotted against the maximum illuminance provided by the installation. The data are taken from Newsham and Veitch (2001) (reference 7) and Boyce et al, 2003b (reference 11)

5. Developments in mesopic photometry

5.1 Mesopic vision

For all the photometric quantities used in the measurement of lighting, the conversion from radiometric units to photometric units is done using the CIE Standard Photopic Observer. This is a smoothed approximation to the brightness response of the fovea at modest light levels. (Viikari et al., 2005) The use of the CIE Standard Photopic Observer for all light measurement poses a problem for some exterior lighting applications because as light level is reduced different photoreceptors are active in different parts of the retina. Specifically, as the adaptation luminance falls below about 3 cd/m^2 (photopic) the rod photoreceptors escape from the grip of the cone photoreceptors and begin to become influential. Their influence continues to grow until as the adaptation luminance falls below about 0.001 cd/m^2 (photopic), the cone photoreceptors cease to function and the rod photoreceptors are all that are left to serve vision. Vision where both cone and rod photoreceptors are active is called mesopic vision

As a consequence of the existence of mesopic vision the spectral sensitivity of the visual system changes and that change is different for different parts of the retina. Ironically enough, for the fovea there is no change. The CIE Standard Photopic Observer still applies to the fovea 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 and eccentricity, until either rods dominate, as in scotopic vision, or cones dominate as in photopic vision.

5.2 Applications

Mesopic vision is important for road lighting, security lighting and emergency lighting because the lighting conditions produced tend to straddle the mesopic / photopic boundary. Nonetheless, all the photometric quantities that characterize such lighting use the CIE Standard Photopic Observer. This practice can lead to situations where the photometric measurements bear little relation to the visual effect of the light source.

Whereas the CIE has produced recommendations for the spectral response of the fovea in the photopic state, the CIE Standard Photopic Observer, and for a much larger area in the scotopic state, the CIE Standard Scotopic Observer, it has not been able to develop a system of mesopic photometry. This is not for want of trying (CIE 1989). Indeed several different systems have been suggested, most using the perception of brightness as a criterion and based on some weighted combination of photopic and scotopic measurements to achieve a transition from the Standard Photopic Observer to the Standard Scotopic Observer. Others have abandoned the perception of brightness as the metric of visual effect and, using reaction time, have developed a comprehensive system of photometry that covers photopic, mesopic and scotopic light levels (Rea et al, 2004). Yet others claim that, because of the continuously shifting spectral sensitivity of the periphery, no true system of mesopic photometry is possible (Clear and Berman, 2006). Whatever the ultimate fate of mesopic photometry, there is no doubt that visual performance is modified on changing from photopic vision to mesopic vision.

5.3 Performance in mesopic vision - Laboratory studies

The simplest place to start this discussion of the impact of mesopic vision is in the laboratory where the the visual field can be lit uniformly to the same luminance, with light of the same spectrum. He et al. (1997) carried out such a laboratory experiment in which high pressure sodium and metal halide light sources were compared for their effects on the reaction time to the onset of an achromatic 2° disc, either on axis or 15° off-axis, for a range of photopic luminances from 0.003 cd/m^2 to 10 cd/m^2. The luminance contrast of the disc against the background was constant at 0.7. Figure 8 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 subjects. From Figure 8 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 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 metal halide lamp at the same photopic luminance, and the magnitude of the divergence between the two sources, increases as the photopic luminance decreases.

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 metal halide lamp produces shorter reaction times for off-axis detection than the high pressure sodium lamp in the mesopic range because the spectral power distribution of the metal halide lamp is more effective in stimulating the rod photoreceptors. It is also evident why there is no difference between the two light sources for on-axis reaction times.

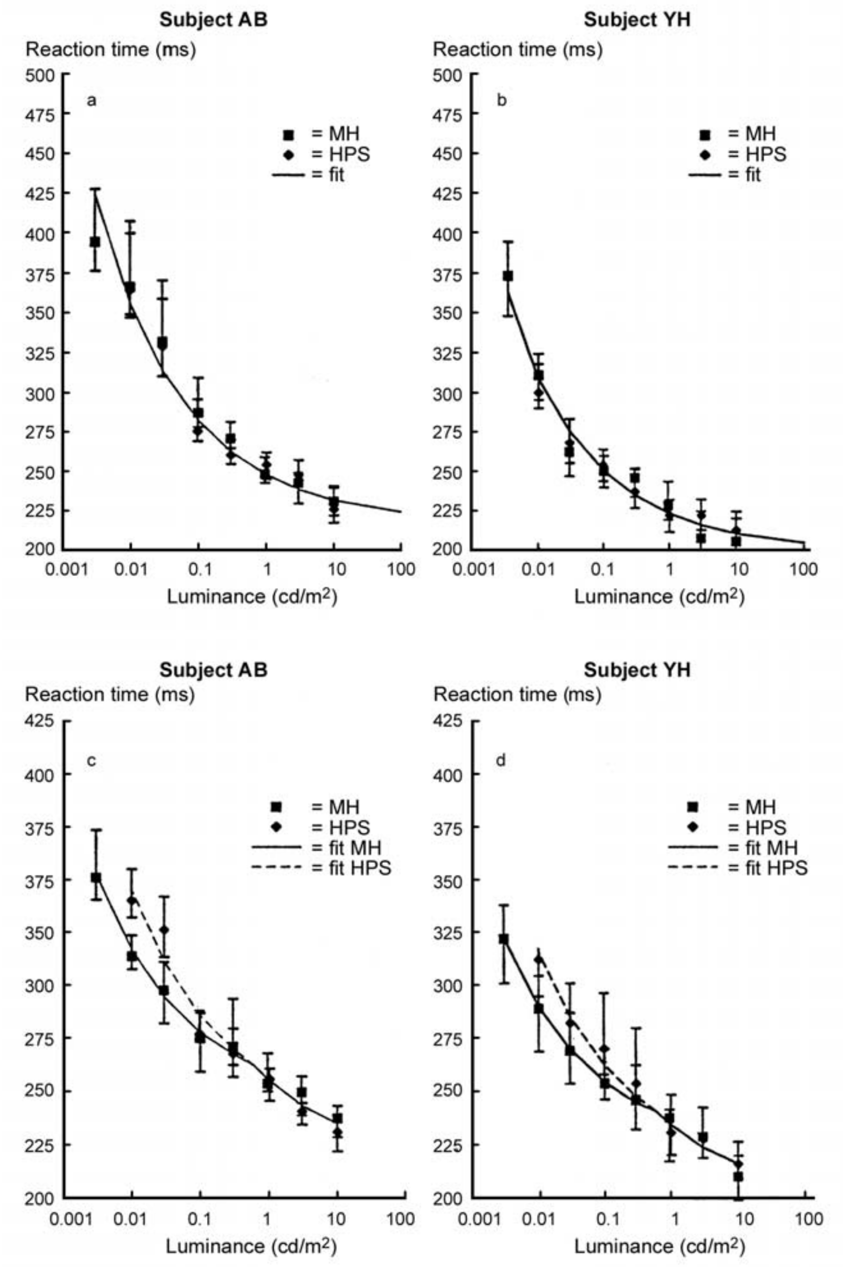

Figure 8. Median reaction times, and the associated interquartile ranges, to the onset of a 2 degree, high contrast target seen either (a and b) on-axis or (c and d) 15 degrees off-axis, and illuminated using either high pressure sodium (HPS) or metal halide (MH) light sources, for photopic luminances in the range 0.003 to 10 cd/m^2 (after He et al, 1997).

Lewis (1999) has obtained similar results using illuminated transparencies. Figure 9 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 used for road lighting; low pressure sodium, high pressure sodium, high pressure mercury, incandescent and metal halide, plotted against the photopic luminance. As long as the visual system is in the photopic range 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 then the different light sources produce different reaction times at the same photopic luminance, the light sources that stimulate the rod photoreceptors more (incandescent, mercury vapour and metal halide) giving shorter reaction times than the light sources that stimulate the rod photoreceptor less (low and high pressure sodium).

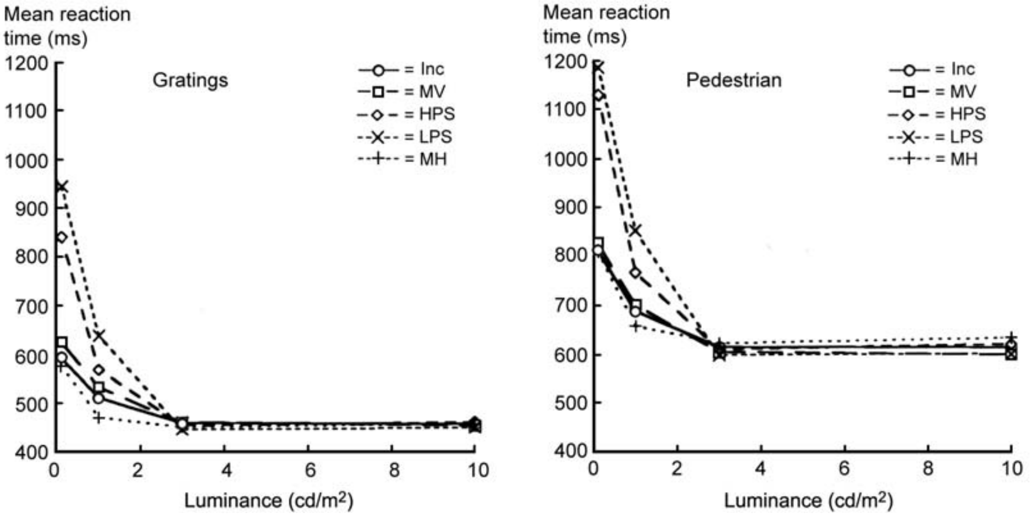

Figure 9. Mean time to correctly identify the vertical or horizontal orientation of a grating and the direction a pedestrian located adjacent to a roadway is facing, plotted against the photopic luminance produced by five different light sources (Inc = incandescent, MV = mercury vapour, HPS = high pressure sodium, LPS = low pressure sodium, MH = metal halide) (after Lewis, 1999)

Lewis (1999) used the same technique to examine the effect of the spectral power distribution of a light source on the time taken to determine which way a women standing at the side of a road was facing. Figure 9 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 produce faster reaction times at the same photopic luminance.

Another approach to evaluating the effect of light spectrum in mesopic conditions measured the probability of detecting the presence of a target off-axis. Bullough and Rea, (2000) used a simple driving simulator based on the projected image of a road, controlled through computer software. The subject could control the speed and direction of the vehicle along the road through a steering wheel and accelerator. A computer monitored the time taken to complete the course and the number of crashes occurring. Filters were applied to the projected image of the course to simulate the light spectrum of both high pressure sodium and metal halide lighting and more extreme red and blue light, for a range of luminances. Interestingly, there was no effect of light spectrum on the time taken to complete the course, i.e., on driving speed, but there was a marked effect on the ability to detect the presence of a target near the edge of the roadway. The light spectra that stimulated the rod photoreceptors more (blue and metal halide) led to a greater probability of detection than light spectra that did not stimulate the rod photoreceptors so effectively (red and high pressure sodium).

Another application where something other than photopic vision is required is emergency lighting. Mulder and Boyce (2005) report a study in which people were asked to find their way through a room containing a number of large black boxes, immediately after the normal lighting was extinguished leaving only emergency lighting. Figure 10 shows the mean performance metric, this being a combined measure of speed over the escape route and the number of collisions, plotted against log scotopic illuminance, for different light sources with different spectral power distributions, It is clear that scotopic luminance is a good predictor of the ability to move over the escape route although it must be admitted mesopic luminance was just as good, Both scotopic and mesopic illuminance were better than photopic illuminance.

5.4 Performance in mesopic vision - Field studies

The laboratory studies discussed above leave little doubt that, for detecting off-axis targets, using light sources that more effectively stimulate the rod photoreceptors is advantageous when the visual system in the mesopic state. But is the advantage retained in the field where both luminances are much less uniform? Akashi and Rea (2001) had people drive a car along a short road while measuring their reaction time to the onset of targets 15 and 23 degrees off-axis. The lighting of the road and the area around it was provided by either high pressure sodium or metal halide road lighting, adjusted to give a similar amount and distribution of light on the road, and seen with and without the vehicle's halogen headlights on dipped beam. There was a statistically significant difference between the high pressure sodium and metal halide lighting conditions but no statistically significant effect of the halogen headlights. Specifically, the mean reaction time to the onset of the targets was shorter for the metal halide lighting than for the high pressure sodium lighting at both eccentricities (Figure 11).

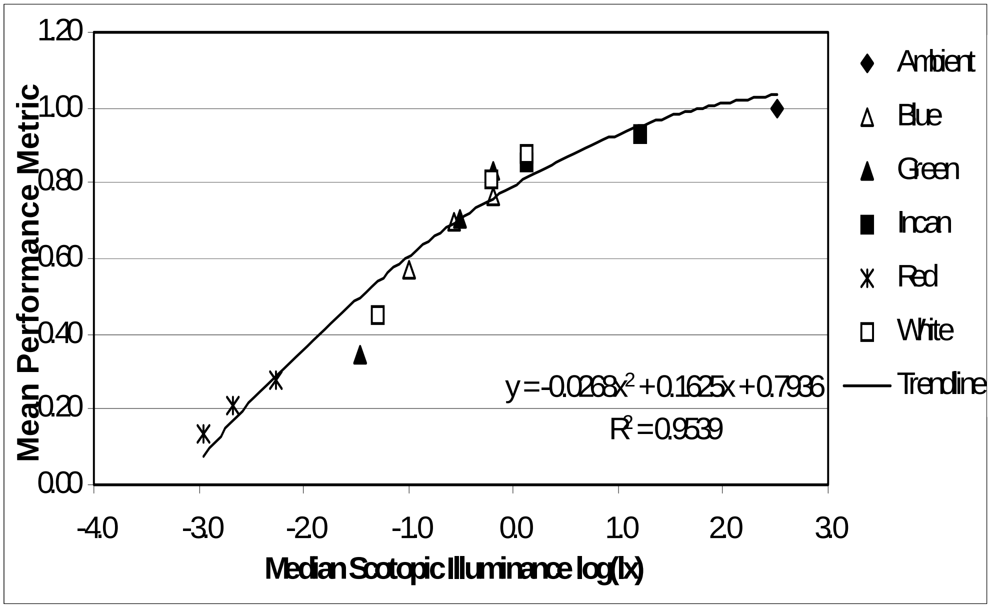

Figure 10. Mean performance metric plotted against log median scotopic illuminance for a number of light sources with different spectral power distributions (from Mulder and Boyce, 2005).

5.5 Implications for practice

The implications of mesopic vision for emergency lighting are clear. At the same luminance, light sources that stimulate the rod photoreceptors more give better emergency lighting. However, the implications for road lighting are rather more complex. Specifically, the benefit of choosing a light source that stimulates the rod photoreceptors more depends on the driver's adaptation luminance and the balance between on-axis and off-axis tasks. Provided the adaptation luminance is such that the visual system is operating in the photopic state there is no effect of light spectrum on off-axis reaction time. If the adaptation luminance is in the high mesopic, say about 1 cd/m^2 (photopic), the effect of light spectrum is slight. It is only when the adaptation luminance is well below 1 cd/m^2 (photopic) that the choice of light source is likely to make a significant difference to off-axis visual performance. How often this occurs is open to question. Current road lighting standards recommend average road surface photopic luminances in the range 0.3 to 2 cd/m^2 in Europe (CEN, 2002) and 0.3 to 1.2 cd/m^2 in the USA (IESNA, 2000a). Such luminances are close to the conventional upper end of mesopic vision and most are above the upper limit of a recent model of unified system of photometry in which the start of the mesopic is at 0.6 cd/m^2 (Rea et al, 2004) This suggests that where there is good quality road lighting there is little benefit to be gained from using light sources that more effectively stimulate the rod photoreceptors, at least as regards the reaction times to off-axis targets. The same conclusion applies to on-axis detection. Several studies have been made of the effectiveness of different 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). All the measurements were made directly viewing the object, i.e., the retinal image fell on the fovea of the retina.

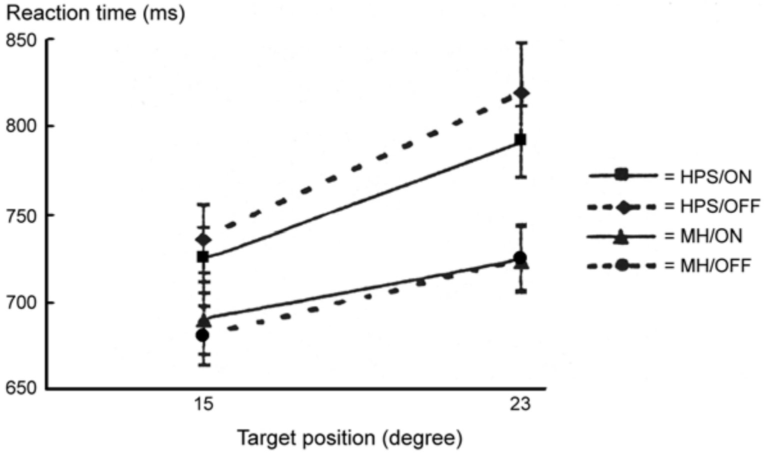

Figure 11. Mean reaction times (and the associated standard errors of the mean) to the onset of a target at 15 degrees and 23 degrees off-axis while driving, with high pressure sodium (HPS) and metal halide (MH) road lighting, and with halogen headlights turned on and off. The road lighting using the 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 and Rea, 2001)

Unfortunately for simplicity, another approach to quantifying the effect of mesopic vision on driving has recently been published (Eloholma and Halonen, 2006). The relevant points about this approach are that it is based on performance on a battery of tasks claimed to be relevant to driving and it shows mesopic effects up to 10 cd/m^2. If this approach really applies to driving then there are likely to be benefits in choosing light sources for road lighting that are more effective in stimulating the rod photoreceptors. For example, according to the Eloholma and Halonen (2006) model, road surface luminances of 1 cd/m^2 (photopic) provided by either high pressure sodium or metal halide light sources are actually mesopic luminances of 0.94 cd/m^2 for high pressure sodium and 1.10 cd/m^2 for metal halide light sources. This implies that road lighting standards expressed in mesopic luminance rather than photopic luminance would give different weightings to these two light sources.

6. Developments in light and health

For most of the last century, light has been considered solely in terms of its impact on our ability to see. However, over the last decade, the impact of exposure to light on human health has begun to be appreciated. 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. Current knowledge about the impact of light exposure on human health is very variable. Some effects are well established but there remain many unanswered questions.

6.1. Established effects of light on health

There can be no doubt that exposure to light can have both positive and negative effects on human health. Vitamin D is produced by the incidence of optical radiation on the skin. Vitamin D is essential for healthy bones and influential in many other aspects of health (Holick, 1985, 2005). However, optical radiation incident on the skin and eye is also known to produce tissue damage, both acute and chronic, through either thermal or photochemical routes. There exist occupational safety guidelines limiting the exposure to optical radiation (ACGIH, 2004) and methods of evaluating electric light sources for their potential to cause tissue damage (IESNA, 1996)

There is also evidence that some patterns of light exposure can alleviate problems associated with diminished operation of the circadian system. For example, people with Alzheimer’s disease show a fractured sleep / wake cycle, often being active at night. It has been shown that exposure to bright light during the day and little light at night restores the sleep / wake cycle to a more stable state (van Someren et al., 1997) (Figure 12).

Similarly, some people suffer from timing problems with sleep, young people having delayed sleep phase syndrome and old people having advanced sleep phase syndrome. Exposure to bright light at the correct time has been shown to correct these timing problems, the exposure being in the morning for the young and the evening for the old (Czeisler et al., 1988; Campbell et al., 1993).

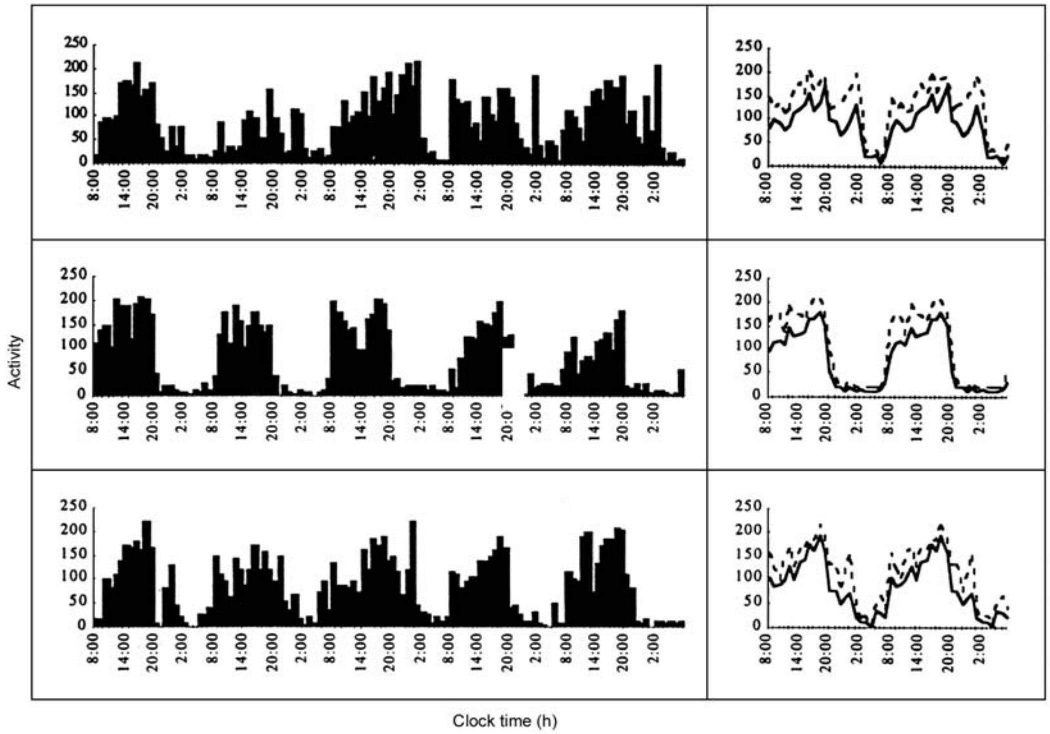

Figure 12. Raw hourly activity data of a patient with Alzheimer's disease over five days, before (upper panel), during (middle panel) and after (lower panel) bright light treatment. The right panels show the average activity levels over 48 hours for 22 subjects with various forms of dementia for the same light exposure conditions (after Van Someren et al., 1997)

There is also the presently unexplained phenomena of the use of light treatment to overcome seasonally affective disorder (SAD), a condition in which people feel depressed during a specific season, usually winter, but not during the rest of the year. Exposure to bright light has been shown to diminish this depression in a significant number of people (Lam and Levitt, 1999).

Thus, there is no doubt that light exposure can influence human health, for good or bad. The effects of optical radiation on the skin are well understood. What are not well understood are the effects of light operating through the eye and hence through the circadian system. What we need to know can be identified by asking three sorts of questions. Fundamental questions related to the complexity of the nervous system; specific questions about the most efficient way of stimulating the circadian system; and questions of application. Each of these will be discussed in turn.

6.2 Fundamental questions

The study of the non-visual effects of light entering through the eye has been concentrated on the pathway from the retina through the suprachiasmatic nuclei (SCN) and then by way of the paraventricular nucleus (PVN) and the superior cervical ganglion to the pineal gland (Figure 13).

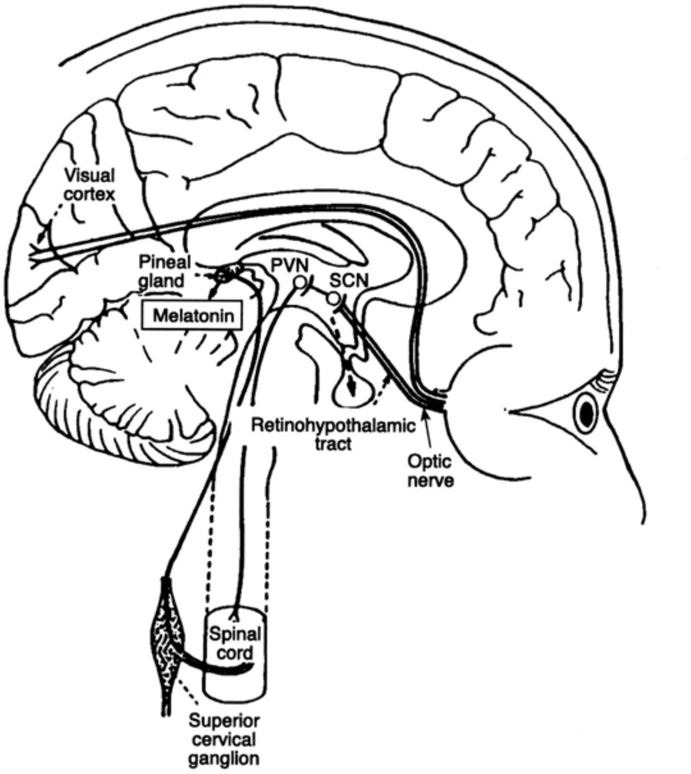

Figure 13. A simplified illustration of the retinohypothalamic-pineal axis (from IESNA, 2000b)

In dark conditions, the pineal gland synthesizes the hormone melatonin, which is circulated throughout the body by the bloodstream as a marker of time. The change in melatonin concentration and the phase shift in melatonin following exposure to light have been used to define the absolute and spectral sensitivities of the circadian system.

The problem that arises with this approach is not to do with the quality of such studies but rather with the fact that they are examining only one impact of circadian system. The evidence for this is anatomical, physiological and psychological. Anatomical studies have shown that the SCN, which is believed to be the central clock, are connected to many other parts of the brain such as the thalamus, posterior pituitary, septum, and midbrain (Klein et al., 1991). These parts regulate the production of a wide range of hormones and hence are likely to influence many different physiological functions. Physiologically, light received at the retina has been shown to influence core body temperature, heart rate and the production of the hormone cortisol (Bailey and Heitkemper, 2001). Psychologically, light received at the retina has been shown to affect alertness (Cajochen et al., 2000). Clearly, the circadian system operates at a very basic level of human physiology and there is still much to learn about its influence.

Another way to exposure the limitations of current knowledge is to ask whether the use of light operating through the circadian system has any negative side effects. That negative side effects can occur following the deliberate exposure to light is evident from the warnings associated with the use of light exposure to treat SAD. While exposure to illuminances at the eye of 10,000 lx for 30 minutes are recommended for the treatment of SAD (Lam and Levitt, 1999), mild disturbances of vision and headaches that subside with time may also occur. Further, warnings have been given that, when proposing such treatment, care should be taken with patients who have a tendency towards mania, whose skin is photosensitive or who already have retinal damage and who have a medical condition that makes retinal damage likely (Levitt et al., 1993, Gallin et al., 1995; Kogan and Guilford, 1998). Other plausible side effects, including the development and growth of cancers and neurodegenerative diseases, have been identified as a consequence of melatonin suppression following light exposure at night (Reiter, 2002; Blask et al., 2002 and 2005). At the very least, such findings suggest the need for caution in encouraging the widespread use of light as a means of enhancing human health.

6.3 Questions of efficiency

Even if the above warnings are ignored, there remain a number of questions that need to be answered if light is to be used efficiently to stimulate the circadian system. They relate to such aspects as spectral sensitivity, the relative sensitivity of different parts of the visual field, whether there is any adaptation effect, as there is in the visual system; how light exposure is integrated over time, and the significance of the timing of light exposure. Each of these questions will be considered in turn.

To design a light source that is efficient in stimulating the circadian system, it is first necessary to know the spectral sensitivity of the circadian system. Careful measurements of this have been made using single wavelength exposures and a constant criterion approach with melatonin suppression as the marker (Brainard et al., 2001; Thapan et al., 2001) (Figure 14).

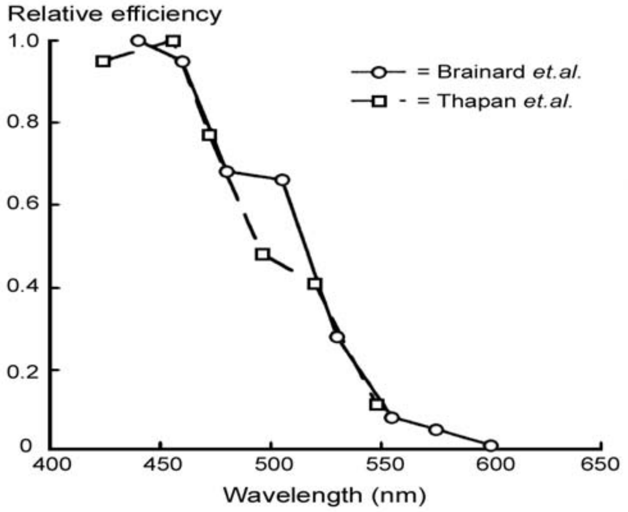

Figure 14. Measured relative efficiency of electromagnetic radiation at different wavelengths in stimulating the human circadian system, using melatonin suppression as a marker (after Brainard et al., 2001, and Thapan et al, 2001)

These measurements have shown a strong sensitivity to short-wavelength optical radiation with a peak sensitivity about 465 nm that is very different from the peak sensitivity at 507 nm and 555 nm of the scotopic and photopic visual system. More recently, evidence has been produced that there is an element of opponency in the spectral sensitivity, which means that it will not be possible to predict accurately the efficiency of multi-wavelength light sources for stimulating the circadian system from a spectral sensitivity curve based on single wavelength exposures (Figueiro et al., 2004). Very recently, a model of phototransduction has been produced based on the known neuroanatomy and physiology of the human visual and circadian systems and that can fit both the single and the multi-wavelength data (Rea et al., 2005). This model has not yet been independently tested but, if correct, it does imply that the circadian system has different spectral sensitivities for light sources with different spectral content. Until this question of spectral sensitivity is resolved, it will not be possible to develop an efficient light source for stimulating the circadian system.

Another question relevant to efficiency is the significance of different parts of the visual field to circadian stimulation. It is usually assumed that the all parts of the visual field contribute equally to the signal sent from the retina to the SCN. However, this may not be so. Glickman et al. (2003) have shown that the lower half of the retina produces greater suppression of melatonin than the upper half, for the same light exposure. This implies that the upper part of the visual field will make a greater contribution to the signal to the circadian system. If this is so then the efficient stimulation of the circadian system requires that light be preferentially distributed to the upper part of the visual field. Unfortunately, what constitutes the upper part of the visual field depends on the direction of gaze. If the direction of gaze is predominantly downward towards a desk then the upper part of the visual field in a room is formed by the walls, while if the direction of gaze is straight ahead at a screen the upper part of the visual field is formed by the walls and ceiling. Identifying the importance of different parts of the visual field for circadian stimulation and the predominant directions of gaze are important for the design of efficient circadian lighting.

Yet another question that needs to be addressed is whether or not there is an element of adaptation in circadian stimulation. The thought behind this question is that it is the cycle of alternate light and dark that entrains the circadian system. But what constitutes light and dark? Is there an absolute irradiance below which it is always dark and above which it is always light, or is it simply the ratio between light and dark that is effective? If the former is true then there is some minimum irradiance required for efficient circadian stimulation. If the latter is true then it might be possible to achieve efficient circadian stimulation by using a low light level for light and complete darkness for dark. There is limited support for both views. For example, several studies have shown that illuminances in the scotopic range do not show any measurable entrainment or melatonin suppression (McIntyre et al., 1989; Aoki et al., 1998; Zeitzer et al., 2000; Rea et al., 2002). This suggests that illuminances in the scotopic range are effectively dark. On the other hand, there is some evidence that the recent history of exposure to light can influence the sensitivity of the circadian system (Smith et al., 2004).

Another characteristic of the circadian system that differentiates it from the visual system is its time constant. The visual system is an image processing system that operates on a time scale of parts of a second. The circadian system is not an image processing system but more like a simple photocell with a very long time constant of parts of an hour. This implies integration over time thereby making dose the meaningful measure of circadian stimulation. The use of dose implies reciprocity, in that irradiance can be traded off against time. The problem here is that at some point reciprocity breaks down. Where that might be for the human circadian system is not known.

Finally, it is necessary to consider the importance of the timing of light exposure. That timing can matter is evident from the phase shifting effects of light exposure. What this means 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 twenty-four hours (Figure 15).

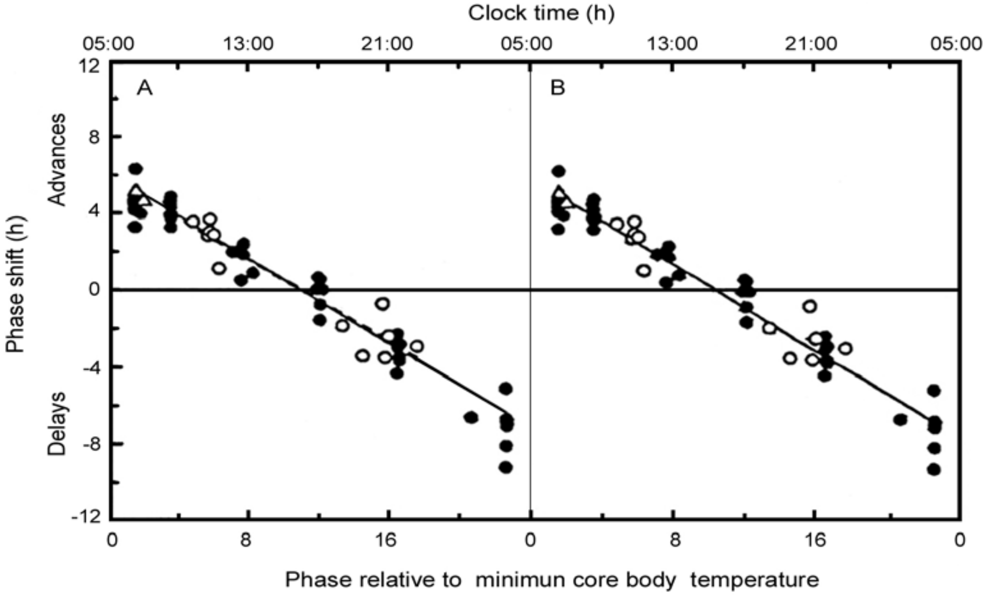

Figure 15.Two cycles of a phase response curve for humans. The horizontal axes show the actual clock time and the time relative to the minimum in core body temperature. The vertical axis shows the phase shift in hours, measured as the change in time of occurrence of minimum core body temperature following exposure to bright light. Exposure to bright light can advance or delay the phase of the circadian rhythm depending on the timing of the exposure relative to the timing of the minimum core body temperature (after Jewett et al., 1997)

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. For healthy young people, whose circadian system is entrained by a regular light-dark cycle, this minimum occurs about 1 to 2 hours before awakening (Jewett et al., 1997). This phase shifting effect has been used as a means for more rapid adjustment to and from night shift work (Crowley et al., 2003) and for overcoming jet-lag (Houpt et al., 1996). However, the significance of the timing of light exposure for many other outcomes remains to be determined.

6.4 Questions of application

There will be many questions about specific applications of lighting for health but there are three that apply to all applications. They concern how precise the application of light needs to be; what is the effect of light exposure outside the period of treatment; and whether the use of light for health is effective for everybody or only for people with particular medical conditions.

The question of precision arises because the circadian system, unlike the visual system, is not required to make fine discriminations of detail and location. The circadian system merely has to be able to distinguish between night and day. Zeitzer et al. (2000) have established a dose-response relationship for 6.5 hours exposure to different illuminances provided by Cool White fluorescent lamps, using the phase shifting and suppression of melatonin as markers of the state of the circadian system. Figure 16 shows the phase shift in melatonin concentration and the percentage melatonin suppression plotted against the illuminance at the eye.

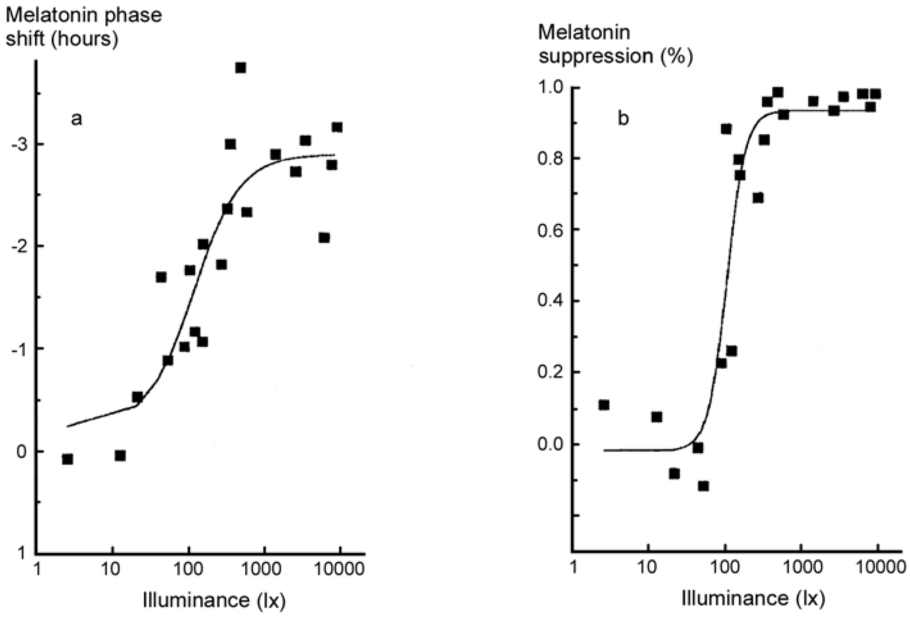

Figure 16. The effect of illuminance at the eye on (a) circadian phase shift of melatonin concentration and (b) percentage melatonin suppression, for six and one half hours of light exposure centered three and one half hours before the core body temperature minimum (after Zeitzer et al., 2000)

The phase shift saturates, i.e., reaches 90 percent of the asymptotic maximum, at an illuminance of 550 lx while the half-saturation response is produced by an illuminance of about 100 lx. For melatonin suppression, saturation occurs at about 200 lx and the half saturation occurs around 100 lx. Similar results have been found by Brainard et al. (1988). Yet others have shown that, given a long exposure time, illuminances of the same order as those found in conventional lighting installations can delay the onset time for melatonin (Wehr et al., 1995), have an acute effect on alertness (Cajochen et al., 2000) and phase shift the sleep-wake cycle (Boivin and James, 2002). Taken together, these results imply that, given a long enough exposure time, illuminances that occur in everyday electric lighting installations can be enough to influence the human circadian system. However, the half saturation illuminances given above indicate that most interior electric lighting installations will fall somewhere on the rapidly rising part of the curve. This, together with the finding of Dawson and Campbell (1990) that the amount of light reaching the retina can vary dramatically in most lit spaces, depending on the light distribution, the reflectance of the surfaces and the direction of gaze, indicates that considerable care will be needed to ensure a reliable effect of electric lighting on the circadian system unless much higher illuminances than those currently recommended for visibility are used.

Another aspect of real-life application is that people in nominally the same situation are likely to be exposed to very different patterns of light and dark over twenty-four hours. For example, an office worker who goes for a walk outdoors at lunchtime will be exposed to a much higher illuminance for a short time than someone who stays indoors, although even outdoors, the actual illuminance received at the eye will depend on whether or not the individual is wearing sunglasses. Similarly, the illuminance of the eye of someone who sits near a window is likely to be much higher during the day than someone who sits far from a window, provided the blinds are not drawn. This would not matter if it were clear what the effects of complex patterns of light exposure are. There exist several different models addressing this problem based on the phase shift of circadian system (Kronauer et al., 1999) but none on other outcomes. Until, there are, it would be wise to note that the successful demonstrations of the effects of light exposure on phase shifting have involved control of light exposure over the whole twenty-four hours (Czeisler et al., 1990; Eastman et al., 1994; Crowley et al.,

2003) but where this has not been possible, the results are more equivocal (Bjorvatn et al., 1999).

Finally, there is the question as to whether the impacts of light exposure on health are confined to those who have a fragile circadian system or who live under a very restricted light profile, or is light valuable for everyone, even the healthy. It is notable that many of the effects of light on health that have been demonstrated so far have been confined to people with fragile circadian systems, e.g., the treatment of advanced and delayed sleep phase syndromes (Czeisler et al. 1988) and the restoration of stable sleep-wake cycles for Alzheimer's disease patients (van Someren et al., 1997) and even where the involvement of the circadian system is not certain, e.g., the treatment of SAD, the people benefiting from light exposure are suffering from a recognized medical condition. It is also notable that all people experiencing prolonged constant light exposure experience undesirable symptoms. Yet some people who live at extreme latitudes seem unaffected by the lack of light. Whether or not this is due to the pattern of electric light exposure entraining the circadian system or some other cue being used in not known. While there is no doubt that light exposure is a valuable and effective treatment for some diseases and infirmities, there is only limited evidence that it can influence the well-being of the healthy. There is no doubt that exposure to bright light at night can induce a greater sense of alertness in the healthy (Cajochen et al., 2000), and if there is something to be done, this may produce a perception of greater well-being. Similarly, Partonen and Lonnqvist (2000) have shown that apparently healthy people report greater vitality, alertness and improved mood following exposure to higher illuminances. Such effects of light on well-being deserve more detailed study.

6.5 Implications for lighting practice

There is no doubt that light exposure affects human health but there is still much to learn about how this occurs, and where to strike the balance between the its advantages and disadvantages. However, it is already possible to develop some guidance about how knowledge in this rapidly growing field might be applied.

One obvious application is in the lighting of homes for seniors. Older people are much more likely to suffer from advanced sleep phase syndrome and Alzheimer's disease. Exposure to bright light during the evening will delay the phase of the sleep / wake cycle and exposure to bright light during the day has been shown to make the sleep / wake cycle of Alzheimer's patients more regular. But there is more to it than simply providing bright light. Older people are also much more likely to be partially sighted so the bright light needs to be provided in such a way that there is no glare and no sudden changes in illuminance. Further, the décor needs to be designed to provide high contrast on salient detail.

Another possible application is to use light to make the transition to and from night shift work easier. For such an application to be successful, it is necessary to control light exposure over the twenty-four hours of the day. Given that this can be done, then more rapid adjustment is possible by exposure to bright light at the appropriate time but lurking in the background is the finding the cancer tumours grow more rapidly when melatonin is suppressed. Until this risk is clarified, it would be unwise to use bright light to suppress melatonin at night, either to increase alertness among night shift workers, unless used infrequently, or to make adjustments to the circadian clock of rapidly rotating shift workers.

The area of greatest interest to lighting practice as regards health is the impact of lighting on healthy people exposed to it during the day. Unfortunately, this is also the area of greatest uncertainty. Melatonin is at a minimum during the day so any effects of light exposure have to operate through a different route, but one thing is generally agreed. It is that the human circadian system developed to respond to the natural variation of day and night. The implication is that exposure to daylight, or an electric light source simulating daylight by effectively stimulating all the photoreceptors in the retina during the day, is desirable. This belief is likely to generate a demand for more daylight in workplaces and in homes. How to meet this demand without causing visual or thermal discomfort or placing additional burdens on other building services will soon be a dilemma facing the lighting industry. As for electric light sources that stimulate all the photoreceptors, the problem there is less to do with discomfort and energy and more to do with the acceptability of the colour appearance of the light.

7. The future

By now it should be clear that this is an exciting time to be active in lighting practice and lighting research. Technology is offering us new light sources and controls that have the potential to allow variations in the amount, spectrum and distribution of light provided, on demand. Research is showing a wider range of impacts of exposure to light, both visual and non-visual, and is gradually recognizing the fact that for the effects of light that operate through psychology rather than physiology, it is necessary to consider the whole environment and not lighting alone (Veitch, 2001 a and b).

The developments discussed above have been chosen because they imply major changes in current lighting practice but there are other developments under way, either smaller in scale or less certain, that are of interest for the future. For example, the design of luminaires may be affected by the evidence that it is possible to generate feelings of discomfort from luminaires overhead, even when they are outside the field of view (Boyce et al, 2003c). There is also a lot of work being done on the use of lighting for electricity load shedding when peak demand threatens the network or when the price becomes too high. Specifically, interest is focused on how far the illuminance in offices can be slowly reduced before the decrease is noticed and how large a decrease is acceptable (Akashi and Neches, 2004). The search for a better measure of colour rendering is also active. The problem is that the CIE General Colour Rendering Index reduces the complexities of colour to a single number. Inevitably, it is a crude measure that fails to discriminate between numerous current light sources and one that will become of even less value with the introduction of multiple narrow band LED light sources (Guo and Houser, 2004; Sandor and Schanda, 2006). Finally, the search for an effect of lighting the space through organizational efficiency rather than individual task performance is underway.

In addition, outside forces are beginning to influence lighting practice. Concern with global warming, fuel depletion, sustainability and light pollution are all influential and will, inevitably, throw up demands for changes to existing lighting criteria and the development of new ones. Knowledge as to how people and lighting interact is fundamental to reach rational decisions about lighting requirements in the face of conflicting interests. What this means is that developments in the human factors of lighting will continue. We live in interesting times.

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