Visual discomfort indoors

PR Boyce PhD[b] and **A Wilkins** DPhil[a]
[a]Department of Psychology, University of Essex, Colchester, UK
[b]Lighting consultant, 60 Riverside Close, Bridge, Canterbury, UK

Visual discomfort refers to discomfort or pain in or around the eyes, often associated with headache and/or nausea, and sometimes accompanied by signs such as red, itchy or watering eyes. The lighting conditions likely to cause visual discomfort are insufficient light for the task at hand, dramatic differences in illuminance around the task, shadows, veiling reflections, glare and flicker. To date, research on visual discomfort has been largely reactive, i.e. in response to complaints, but there is now proactive work that explores why discomfort occurs. The hypothesis underlying this work is that the human visual system has evolved to extract information from the natural world efficiently so that when the visual environment departs from the temporal, spatial or chromatic characteristics of the natural world, discomfort is likely because of inefficient neural processing. An important implication is that visual discomfort therefore depends on both the lighting and the décor of a space. Until this approach becomes more established, visual discomfort can be minimised by following carefully developed standards and guidance, by using products that meet appropriate standards, by paying attention to both lighting and décor and by being aware of the wide variation in individual sensitivity.

1. Introduction

Every biological system has it limits and the visual system is no exception. There are limits to the range of wavelengths and luminances over which vision is possible;[1,2] to the size and contrast of detail that can be resolved;[3] to how well colours can be discriminated[4] and to the temporal variations that can be detected.[5] When the visual system is required to operate close to these limits for a prolonged period, people may operate less efficiently, often with signs and symptoms of discomfort. Typical signs are red, itchy or watering eyes. Typical symptoms include pain in and around the eyes, headaches, nausea and fatigue. Such signs and symptoms can be produced by many factors, both physiological and psychological,[6,7] so care has to be taken when identifying the cause of any discomfort.

Complaints of visual discomfort have two distinctive features. First, they are characterised by large individual differences in reactions to the same stimulus.[8] Part of this individual variability results from discrimination of comfort from discomfort and part results from variation in the acceptability of any discomfort (i.e. the degree of discomfort tolerated before complaint). For lighting, the discrimination is likely to be determined by the characteristics of the visual system, which inevitably includes some individual variability, but the criterion of acceptability adds another layer of variability. The criterion is based on past experience and hence on expectations and attitudes. Note that visual discomfort is context specific. For example, flicker in an office is considered uncomfortable but in a night club it may be acceptable.

Address for correspondence: A Wilkins, Department of Psychology, University of Essex, Colchester, CO4 3SQ, UK. E-mail: arnold@essex.co.uk

Different people have different experiences and hence different expectations.[9]

The underlying causes of visual discomfort are as follows:

Poor visibility: Any visual task that has stimuli close to detection threshold contains information that is difficult to extract. It is likely that such poor visibility increases the neural demands on visual processing and leads to visual discomfort

Overstimulation: Discomfort can result from overstimulation of the visual cortex by large-field, spatially or temporarily repetitive patterns.[7] Prolonged work in such conditions can result in eyestrain, headaches and fatigue.

Distraction: The human visual system has a large peripheral field that detects the presence of bright, moving or fluctuating objects that are then examined using the small, high-resolution fovea.[10] If such objects in the peripheral field cannot be avoided they become sources of distraction. Having to ignore objects that automatically attract attention can lead to visual discomfort.[11]

While problems with visibility, overstimulation and distraction are the underlying causes of visual discomfort, they tell us little about the aspects of lighting responsible. Fortunately, it is not too difficult to identify the culprits. For visibility, it is a usually a matter of insufficient illuminance or inappropriate light distributions that cause shadows or veiling reflections, or an inappropriate light spectrum where some form of colour discrimination is required. For overstimulation, temporal fluctuations in light output are the obvious culprit but if large areas of high-chroma colour are present, light spectrum may be important because the spectrum can determine how saturated the colours appear. For distraction, discomfort glare is clearly involved.

Despite this list of lighting factors, it is important to note that, apart from flicker, lighting is not the sole culprit involved in visual discomfort. The characteristics of the task and the colours and reflectances of the surrounding surfaces are also involved. For example, by increasing the size or contrast of print what was insufficient light for reading can be made sufficient. Similarly, by increasing the reflectance of the surrounding surfaces, the strengths of shadows, veiling reflections and discomfort glare can all be reduced. This means that visual discomfort is determined by a combination of lighting and environmental design, which is as it should be, given that what the visual system is trying to do is to construct model of its surrounding environment, as revealed by lighting.

2. Lighting conditions likely to cause visual discomfort

The history of attempts to limit the visual discomfort caused by lighting reveals two paths. The first reflects the fact that you do not need scientific evidence to know when you are suffering visual discomfort, although you may not always know the cause. However, for many situations, simple tests such as shielding the eyes from a glare source are enough to identify the cause and a means to limit its occurrence. The second is more recent and is related to the use of electric lighting in all types of buildings and the rising importance attached by society to public health. These developments have led to the publication of standards and general guidance for the designers of lighting installations.[12–15]

2.1. Illuminance

The most obvious lighting condition that can cause visual discomfort is poor visibility. There is a well-developed and independently replicated model of the effect of illuminance on visual performance[16] but this is rarely used

because, in most countries, there exist legally enforceable recommendations for minimum illuminance[13] that far exceed what is necessary to provide effective visibility.[17] In the UK, the first IES Code containing illuminance recommendations was published in 1936, a process that continues today,[15] although the illuminances recommended are now much higher.[18] Most countries have their own illuminance criteria but all show the fluctuations to be expected from the consensus process used in determining the illuminances recommended[19] and have become *de facto* minima. Curiously enough, illuminance criteria specifying maximum illuminances are markedly absent, despite the emphasis in recent years on reducing electricity consumption. There is some evidence for increased discomfort indoors at illuminances above 1000 lux and separate evidence above 2500 lux.[20,21] In their survey of classroom lighting, Winterbottom and Wilkins[22] found that with lights on and blinds closed illuminance exceeded 1000 lux in 39% of classrooms, and in 16% of classrooms the level exceeded 2000 lux.

2.2. Illuminance uniformity

Illuminance recommendations, if correctly matched to the requirements of the tasks, should guarantee good visibility but on their own are not enough to avoid visual discomfort. The distribution of illuminance over space also has to be considered. To do this a uniformity ratio, is recommended, measured as the minimum/average illuminance occurring across a hypothetical working plan. Several studies have shown that for windowless offices a uniformity ratio of 0.7 or greater is desirable.[23,24] However, in large 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. The illuminance uniformity ratio will then be much less than 0.7, but few complaints are heard unless there is a lot of internal obstruction.[25]

The reason for this is probably that the rate of change of illuminance with distance is gradual and as long as there is enough illuminance to provide good visibility, gradual variations are not a cause of visual discomfort. Where visual discomfort may occur is where a dramatic illuminance non-uniformity is evident. This can occur when sharp-edged shadows are cast over the work area or where there are areas of high illuminance adjacent to the work area because these can be a source of distraction. Studies of peoples' reactions to several different forms of local lighting for desks have shown that the most preferred is one that provides a uniform, shadow-free illuminance over the work area and lower illuminances outside that area.[26] The latest European Standard[13] sets out a pattern of relative illuminances for work surfaces and surroundings so as to avoid such distraction.

2.3. Shadows

Shadows are cast when light coming from a particular direction is intercepted by an opaque object. 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. 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.

If an object is big enough, for example a large chemical plant with people working inside it, the shadows cast will reduce the illuminance over a large area and hence reduce the visibility of details that need to be seen. If the illuminance cannot be increased by local lighting but work has to be sustained, discomfort may result. On a smaller scale a shadow pattern can reduce the visibility of the details of the object and cause confusion. An example of this is attempting to work on small electronic components
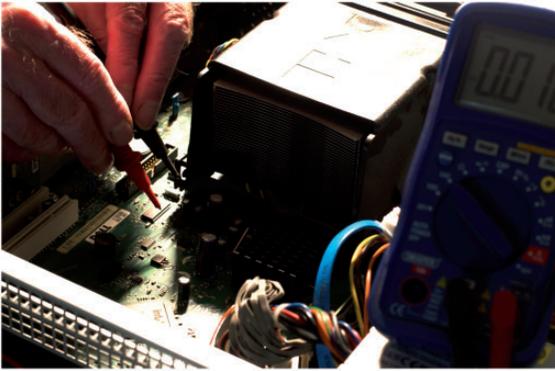
Figure 1 Shadows reducing visibility

inside a box where the lighting causes shadows to be cast over the components (Figure 1).

Although shadows can sometimes cause visual discomfort, it should be noted that they are also useful for revealing the form and texture of three-dimensional objects (Figure 2). Techniques of display lighting are based around the idea of creating shading, highlights and shadows to change the perceived characteristics of the object being displayed.[27,28] Thus, whether shadows cause visual discomfort or enhance the appearance of an object will depend on the context in which they occur.
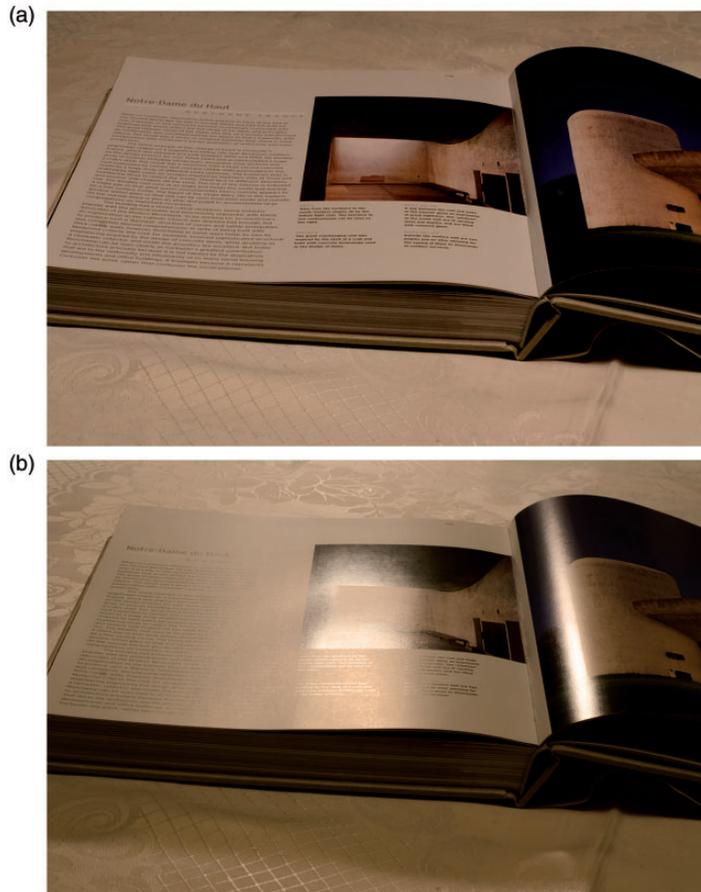
2.4. Veiling reflections

Veiling reflections provide another aspect of light distribution that can sometimes generate visual discomfort. Veiling reflections are luminous reflections from specular or semi-matte surfaces that physically change the contrast of the visual task and hence its visibility. 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. For a specular surface, veiling reflections

Figure 2. Shadows revealing form and texture.

occur at positions where a source of high luminance is at the mirror angle formed by the observer and the object. Veiling reflections are most commonly experienced when looking at a glossy book (Figure 3) but then they can easily be removed by changing the geometry between the light source, book and reader. However, if this geometry cannot be changed and prolonged viewing of low visibility details is required, then veiling reflections can be a source of visual discomfort.

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

Figure 3 A page of a glossy book (a) without and (b) with veiling reflections. Note the reversal of contrast polarity of the print produced by veiling reflections immediately below the photograph in the book

desirable. To complicate matters, the magnitude of veiling reflections, and hence the CRF, can vary dramatically within an installation[29] and, for print, strong veiling reflections can sometimes increase visibility by reversing contrast polarity (see Figure 3). This is why CRF has disappeared from most standards and design guidance.

Although veiling reflections can be considered a negative outcome of lighting that can cause discomfort, they can be used positively, but when they are, they are conventionally called highlights. Display lighting of specularly reflecting objects, such as silver and glass, is all about producing highlights (Figure 4).

2.5. Discomfort glare

When a very high luminance can be seen in the visual field the usual behaviour is to shield the eyes or look away. This behaviour can be taken as an indication that glare is present. Vos[30] has identified eight different forms of glare but only one is commonly experienced indoors – discomfort glare.

Discomfort glare from light sources and luminaires has been studied for almost 60 years.[31–37] Initially, the outcome of this work

Figure 4 Highlights on silver and glass

was a plethora of different national systems for predicting the degree of discomfort glare 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.[14,38] The other is the CIE Unified Glare Rating (UGR) system used everywhere else.[15,39,40] In both methods, increasing the luminance of the glare source, increasing the solid angle subtended by the glare source at the observer's eye, decreasing the luminance of the background and decreasing the deviation of the glare source from the line of sight will all increase the level of discomfort glare.

There are problems with both systems.[41] For real luminaires, there can be difficulties in determining the luminance and size of the glare source because many luminaires, particularly LED luminaires, are not uniform in luminance. 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. There are questions about glare source size

even when the luminance is uniform. Einhorn[42] pointed out that all the glare control systems in use predict intolerable glare for very small sources, such as occur when bare lamps are used in chandeliers, yet these are tolerated very well. 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[32] 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. Neither VCP nor UGR considers the immediate surround, although there is certainly evidence that both the luminance and colour of the immediate surround influence the perception of discomfort glare.[43]

Finally, there is a question about the impact of the deviation of the glare source from the line of sight. Clear[41] compared the original measurements of this effect with some more recent results.[44] The two sets of data do not agree well. Given these uncertainties it should not be surprising that UGR fails to accurately predict peoples' levels of discomfort, particularly for LED luminaires.[45,46] As a result, there have recently been attempts to develop new discomfort glare prediction systems based on what is known about how the visual system operates.[47,48] How successful these will be remains to be seen.

While VCP and UGR were developed primarily for indoor luminaires, a parallel course has been followed for large area light sources such as windows. Windows require a different approach because then light from the glare source affects the state of visual adaptation. A number of different systems for predicting the level of discomfort produced by a bright sky seen through a window have been developed[32,49,50] with varying ease of use. However, it is always worth bearing in mind

that discomfort has a psychological element. Tuaycharoen and Tregenza[51] considered how the nature of the view seen through a window might affect the level of discomfort glare and showed that the same luminance can produce different perceptions of discomfort glare depending on the view seen through the window; the better the view the less the level of discomfort glare. Clearly, there is still much to appreciate about glare.

2.6. Flicker

All electric light sources that operate from an alternating current supply produce regular fluctuations in light output. When these fluctuations become visible they are called flicker. A lighting installation that produces flicker over a large area can cause discomfort. For some people, exposure to flicker can cause seizures.[52]

The main factors that determine whether a fluctuation in light output used for the illumination of a surface will be visible are the time-averaged luminance, the frequency, the percentage modulation and the areal extent of the fluctuation on the illuminated surface.[53,54] The higher is the time-averaged luminance, the larger is percentage modulation and the larger is the area, the more likely it is that a given frequency will be seen to flicker.

There are wide individual differences in sensitivity to flicker.[2] This, together with the fact that electrical signals associated with light fluctuations can be detected in the retina even when there is no flicker visible,[55] implies that a clear safety margin is necessary to avoid discomfort.

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 oscillations in the electricity supply because of the thermal inertia of the filament. Light sources that rely on an electric

discharge to produce light, e.g. fluorescents, have a faster response time, so it is the characteristics of the control gear combined with the persistence of any phosphors used that determine whether a discharge lamp will produce flicker.[56] With older-style electro-magnetic control gear 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. This increase in supply frequency produces both a higher frequency and a smaller amplitude modulation in light output. 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.[57]

The arrival of LEDs has reinvigorated concern about flicker. This is because solid-state light sources have an inherently fast response time, of the order of nanoseconds. The IEEE has recently produced a standard for limiting flicker from solid-state lighting based on a truncated Fourier series.[58,59] Also, Bodington et al.[60] have produced a metric to predict if a given waveform will be seen as flicker. Such guidance is influencing manufacturers to produce more stable, solid-state lighting systems. Currently, only about one-third of tested solid-state light sources comply with the recent IEEE standard. This indicates both that the standard is quite attainable and that there is a need for quantitative testing of LED sources.

3. Current understanding

One central feature of all the lighting research leading to the metrics discussed above is that it has been reactive. In other words, interest has been piqued by complaints about the lighting. Sometimes new standards and guidance have resulted, as is the case for recommended illuminances and veiling reflections. Sometimes the response has been technical, as

in the refinement of luminaire design to reduce discomfort glare and the development of high frequency control gear for fluorescent lamps or better drivers for LED systems. But always the research behind the guidance and the technical developments has been empirical and the result of complaints. However, in the vision research field, some researchers have been trying to establish the reason why some luminous conditions cause visual discomfort and some do not. They take as their starting point the premise that the visual system has evolved to process retinal images from the world of nature. Thus far, they have considered three aspects of natural scenes: temporal, spatial and chromatic. Retinal mages of nature differ from the retinal images of many modern environments in all three aspects. There is little flicker in nature, luminance patterns have a particular spatial structure and colour contrasts are modest.

3.1. Temporal characteristics of visual stimulation

Our eyes examine a scene by making a series of rapid movements between points of interest. We are not usually aware of this movement. This is because the movement is rapid (up to 700 degrees per second) and outside the optimum operating range at which retinal cells can respond to contours.[61] This remains true provided illumination varies only slowly, as in nature. Sunlight reflected from water and interrupted by the leaves of trees provides the only typical sources of flicker in the natural world. In electric lighting systems, however, rapid temporal variation is the norm. When the visual scene is intermittently illuminated and the eyes move, a succession of images, frozen in time with each flash, appears across the retina as a pattern. Under certain viewing conditions the pattern can be seen at flicker frequencies of more than 2 kHz[62] These intrasaccadic percepts have the potential to be confused with the images that appear before and after

the eye movement, and this may be one reason why flicker at 100 and 120 Hz disturbs eye movements across text,[63] interferes with visual performance[64] and results in discomfort and headaches.[56] If so, intrasaccadic percepts may provide a model for the effects of light fluctuations, including those that are too rapid to be visible as flicker. Such percepts are likely to depend upon the size of the saccade, which determines its maximum velocity, the luminance and contrast of the image before and after the saccade, which influence saccadic suppression, the modulation depth of the flicker, which determines the contrast of the intrasaccadic image on the retina, and the temporal frequency, which determines the spatial frequency of the image on the retina. To date, only a few of these parameters have been systematically explored, although it is now known that the visibility of intrasaccadic percepts increases, rather than decreases, as the frequency is increased from 100 to 300 Hz, presumably because the spatial array on the retina then has a spatial frequency at which it is more readily visible.[65] One important implication of this finding is that it is not sufficient to increase the temporal frequency of oscillation until flicker is no longer seen; the relationship between visibility and temporal frequency is likely to be non-monotonic.

3.2. Spatial attributes of visual stimulation

Some of the spatial attributes of a scene can be described in terms of the Fourier amplitude spectrum of the luminance of an image. For images from nature this spectrum shows a decrease in amplitude with increasing spatial frequency (f) that approximately follows a reciprocal law (1/f).[66] As a result, a logarithmic plot of amplitude against spatial frequency typically shows a slope close to −1 (Figure 5).

Juricevic *et al.*[67] created meaningless images from filtered random noise and randomly disposed rectangles. When the images
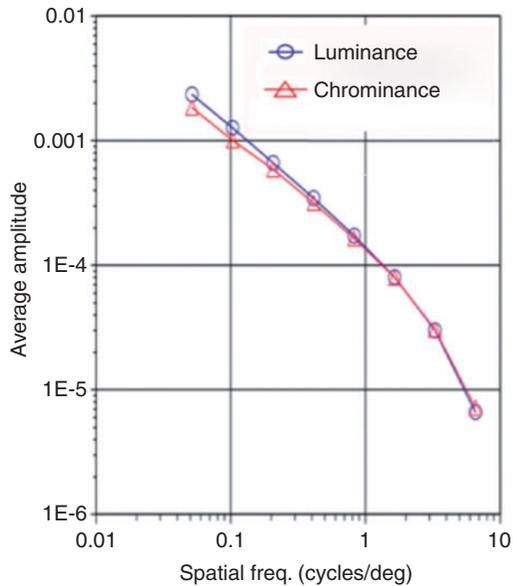
Figure 5 Typical plot of amplitude against spatial frequency for luminance and chrominance of natural scenes[66]

had an amplitude spectrum that approximated 1/f they were rated as more comfortable to look at than images with spectra having steeper or shallower slopes. Fernandez and Wilkins[68] used a wider variety of images including works of art and photographs as well as artificial images formed from filtered noise. They showed not only that images with a 1/f amplitude spectrum were rated as comfortable to look at but also that images with an excess of contrast energy at mid-range spatial frequencies relative to that expected on the basis of a 1/f spectrum were rated as uncomfortable. Selectively reducing the energy at mid-range frequencies was sufficient to make the images comfortable again, suggesting that mid-range spatial frequencies are mainly responsible for discomfort. O'Hare and Hibbard[69] have confirmed these findings. They filtered random noise and showed that visual noise with a 1/f amplitude spectrum was judged more comfortable than any image with a relative increase in contrast energy

within a narrow spatial frequency band ranging from 0.375 to 1.5 cycles/degree.

In all the above studies, the effect of orientation on the amplitude spectrum was not considered. Pennachio and Wilkins[70] pointed out that some of the most uncomfortable (and unnatural) images (viz patterns of stripes) have amplitude spectra with energy that is concentrated in one orientation. Averaging over orientation loses this discriminative feature. They therefore fitted a cone with slope 1/f to the two-dimensional Fourier log amplitude spectra. They obtained the best fit by permitting the mean of the cone to vary but not its slope. The correlations between the residual error and the ratings of discomfort explained a greater proportion of the variance than that explained by the one-dimensional fit used in earlier studies. Across images, ranging from photographs to works of art to artificial images, they were able to explain more than 25% of the variance in judgements of discomfort with a parameter-free model; only small adjustments were necessary to allow for the meridional anisotropy of natural images.

Not only can the 'cone model' predict discomfort, but it also predicts the oxygenation of the cortex in response to images.[71] This suggests that images that are unnatural and uncomfortable demand greater oxygenation. As will now be shown, this is precisely what one might expect from computational models of the visual cortex, which suggest that natural (and comfortable) images are processed efficiently by the neural machinery of the visual cortex, as shown by Field.[72] Uncomfortable images are processed less efficiently, resulting in an increase in neural activity and metabolic demand, as reflected in the greater amplitude of the haemodynamic response.

The human contrast sensitivity function is optimised for encoding images with a 1/f structure.[73] The receptive fields of neurons in the primary visual cortex are such that natural images produce a sparse cortical

response.[73–75] The defining characteristic of this sparse response is that few neurons are highly active and most inactive, thereby reducing metabolic demand. O'Hare *et al.*[76] have used a computational model of visual cortex area V1 to show that uncomfortable stimuli such as striped patterns, which are rare in nature and do not conform to a 1/f structure, result in an excess of 'neural activity' and a non-sparse distribution of 'neural' firing. A more complex model based on that by Li[77] was developed by Penacchio *et al.*[78] and showed a relationship between the sparseness of firing and ratings of discomfort for a wide variety of images. If the neural processing of unnatural and uncomfortable images is indeed inefficient, as these models suggest, then it is to be expected that such images require greater cortical oxygenation.

There are now several studies that indicate a positive relationship between discomfort and neural activation of the visual cortex and therefore (indirectly) with oxygenation. The majority have involved studies of individuals with migraine, many of whom suffer photophobia. Boulloche *et al.*[79] used positron emission tomography and measured the cortical activation in response to three intensities of bright diffuse light. They found activation of the primary and secondary visual cortex in individuals with migraine, but not in controls unless concomitant pain was applied. Huang *et al.*[80,81] used functional magnetic resonance imaging and showed an abnormal blood oxygenation level-dependent (BOLD) response in individuals with migraine, an abnormality that occurred only when uncomfortable striped patterns were observed. Cucchiara *et al.*[82] showed that the amplitude of the BOLD response to a flickering checkerboard correlated with reports of visual discomfort obtained using a visual discomfort questionnaire. A hyperactivation of the cortex in response to uncomfortable visual stimuli has also been observed in individuals who have no history of migraine. Thus, Bargary *et al.*[83] required observers to discriminate the direction of the gap in a Landolt C with a glaring surround of various intensities. They found that the individuals who reported discomfort glare were also those who showed a large BOLD response.

All the above studies have shown a larger haemodynamic response in the visual cortex of individuals who experience discomfort from a visual stimulus. There are also studies of healthy observers that show differences between comfortable and uncomfortable stimuli as regards the amplitude of the haemodynamic response evoked. Haigh *et al.*[84] studied healthy observers and found that stripes with two alternating colours increased in discomfort when the CIE 1976 UCS colour difference between the bars increased. The oxygenation of the visual cortex also increased with the UCS colour difference. The relationship between discomfort and cortical activation therefore occurs for differences between stimuli as well as differences between observers. There is a reciprocity between the computational efficiency with which an image can be processed and the metabolic demand with which it is associated, as revealed by the amplitude of the haemodynamic response. Wilkins and Hibbard[85] have proposed that the discomfort may be a homeostatic mechanism, an aversion that prevents an excessive metabolic load on the visual cortex.

3.3. Chromatic attributes of visual stimulation

Natural scenes rarely have strong colour contrasts.[86] Unsurprisingly, strong colour contrasts can be uncomfortable. Haigh *et al.*[84] demonstrated that as the difference in chromaticity between the bars of a grating increased, so did the discomfort the grating induced. This simple relationship occurred for a number of hues. The relationship between colour contrast and discomfort was best understood in terms of a perceptual colour space (CIE UCS) rather than a

cone-opponent space. The same was true of the oxygenation of the visual cortex in response to the pattern. The larger the chromaticity difference the greater the oxygenation. There have been few studies of visual discomfort from strong colour contrast, although perhaps there should be, given that the colour contrast used in primary schools is often very high (Figure 6).

4. Limiting visual discomfort

The most obvious way of reducing the likelihood of visual discomfort is by following authoritative standards and guidance. These are available in many different forms, from national and international standards with legal force[13] through guidance published by professional bodies[12,14,15] to product comparisons.[87] Standards and professional guidance provide both quantitative and qualitative lighting recommendations for many different applications. Quantitative recommendations for task illuminance, illuminance uniformity and discomfort glare are all common. Qualitative recommendations are usually given for reducing shadows and veiling reflections. The legal or *de facto* legal status of the quantitative recommendations, particularly those that can be easily checked *in situ*, such as task illuminance, ensures they are widely followed but the qualitative recommendations are rarely given the attention they deserve.

Another approach is the development of products that eliminate the cause of discomfort. This is what happened with discomfort glare. The promotion of the UGR system for predicting the level of discomfort glare[40] has encouraged manufacturers to develop luminaires with carefully controlled luminous intensity distributions that rarely cause discomfort glare. At least, this was true until recently. The appearance of many new LED luminaires on the market has caused discomfort glare to become a problem again because UGR does not handle luminaires with a non-uniform luminance pattern well.[46] In the absence of

Figure 6 A primary school classroom (Courtesy of Houlton Construction, Hull)

agreement over how to calculate discomfort glare for non-uniform luminaires, unscrupulous manufacturers feel free to ignore the potential for visual discomfort and maximise the light output of their luminaires by allowing a direct view of the LEDs.

A similar process has been followed for flicker. The use of electronic control gear for fluorescent lamps almost eliminated flicker as a research topic but the arrival of LEDs with their very fast response time has aroused interest again leading to the development of appropriate standards[58,59] and hence better driver design. Comparisons of products by independent organisations as has been done by the US Department of Energy CALiPER (Commercially Available LED Product Evaluation and Reporting) programme have a role to play in ensuring that the market is captured by good quality products that are unlikely to cause visual discomfort.

One feature that is common to both of the above approaches to reducing visual discomfort is that they are focused on lighting rather than the visual environment. Lighting needs to be considered in relation to the visual environment in order to predict discomfort. Different groups of people take responsibility for lighting and for décor and there can be little communication between them. Fortunately, modern technology can be used to rectify this situation. Photometrically accurate computer simulations of visual environments are now available. We know that it is now possible to predict the discomfort from a photographic image[65] and we also know that photographs can be a good surrogate for the real environment in respect of judgements of discomfort.[66] It should therefore be possible to measure the distribution of spatial frequencies for any desired viewing direction, and hence to determine how far they deviate from the desired spatial frequency distribution described in Section 3.2. Until this approach can be refined, the worst situations can be eliminated by taking care

over any stripes in the visual environment. The stripes that are most likely to provoke discomfort subtend more than $3°$ at the eye, have a spatial frequency in the range 1–10 cycles/degree, a luminance contrast that exceeds 10% and a luminance in the photopic range[7] Further, the larger is the CIE colour difference between the component stripes, the greater is the potential for visual discomfort.[79]

Computer simulations can also be used to examine a design for the potential for veiling reflections and uncomfortable shadows on a task. For veiling reflections, a virtual mirror is placed at the task location and then the simulation is adjusted so that the mirror is seen from a likely observer position. If a high luminance source, such as a luminaire, is seen in the mirror, there is a potential for veiling reflections to occur for that observer position if specular material is to be viewed. As for shadows, inserting the task into the simulation should reveal the pattern of shadows and whether these are helpful or disabling.

5. Research needs

There are two general questions that need to be researched if visual discomfort is to be minimised. They are as follows:

> Can the haemodynamic response be used as an objective correlate of visual discomfort to support subjective assessments of discomfort in addition to the muscle tension measures proposed by Berman *et al*?[88]
> What metrics should be used to guide manufacturers and designers of lighting systems and what percentage of the population should the related criteria protect from visual discomfort?

To answer the first question requires a series of validation studies that establish the nature and strength of the relationship between the haemodynamic response and the level of

discomfort produced, over a wide range of lighting conditions and décor. If a significant and reliable relationship can be demonstrated then the haemodynamic response can be used in a converging operations approach to the second question.

The research necessary for metrics and criteria varies between the different causes of visual discomfort. For task illuminance, current recommendations are widely accepted although there are differences in individual preference.[89,90] This suggests that one-size-fits-all lighting will inevitably lead to discomfort for some people.[91,92] Normative data on the percentage of the population experiencing discomfort for a range of realistic activities lit to different illuminances would be useful. This would give the designers of lighting control systems some indications of the likely impact of their proposals.

Illuminance uniformity that varies gradually over a large area is not generally associated with discomfort. Such discomfort occurs when high luminances appear close to the line of sight and cause distraction.[26] Currently, illuminance uniformity is quantified in terms of the ratio of minimum to average illuminance. This is an inadequate description of the stimulus. The rate of change of illuminance and where that change occurs in relation to the task deserve study.

There is plenty of advice available for minimising veiling reflections and shadows and for estimating their consequences for visual performance.[10,12] However, there is limited understanding of the conditions under which veiling reflections and shadows actually cause discomfort. Some research in this area would be welcome.

Discomfort glare has been a research topic for several decades, the outcome being the UGR system. Recently, a number of new glare prediction systems have been developed based on current understanding of the visual system.[47,48] These need to be assessed for the accuracy of their predictions in realistic conditions, especially to what extent they are an improvement over UGR because there is little point in adopting the new systems unless they show a marked improvement. Further investigations of discomfort glare are pointless until there is a much greater understanding of the physiological and psychological aspects of this phenomenon.

Flicker has also been the subject of much recent activity resulting in models of flicker perception.[60] This is useful but insufficient. Discomfort can also be caused by lighting fluctuations that are not visible as flicker. Studies of the individual differences in discomfort and neural activation of the visual cortex in the presence of high frequency light fluctuations are required in order to establish how many people are likely to be adversely affected by light fluctuations of different forms. It seems likely that the rapid motion of the retinal image during a saccade converts temporal variation into a spatial pattern that can sometimes evade saccadic suppression and interfere with visual tasks.

As for the potential of a visual environment to cause visual discomfort, the forms and extent of the departure from the 1/f spatial frequency distribution that are associated with visual discomfort need to be further explored.

6. Conclusion

Visual discomfort is always likely to be with us because, in the words of John Ruskin, '*There is hardly anything in the world that some man cannot make a little worse and sell a little cheaper and the people who consider price alone are this man's lawful prey*.' This means there are always likely to be inferior lighting products and designs on the market and people willing to buy them. This is not a council of despair. By following carefully developed standards and guidance, by using products that meet appropriate standards, by

paying attention to both lighting and décor and by quantifying the wide variation in individual sensitivity, the incidence of visual discomfort can be minimised. All the information needed to follow this advice is not yet in place but with the development of better measures to identify the occurrence of visual discomfort, a greater understanding of its causes, and some carefully focused research, it soon can be. Until it is, there is a lot to be said for renovating lighting systems that are known to cause discomfort and that are still in widespread use. For example, 80% of schools in the UK are still using fluorescent lamps with electromagnetic control gear.[22] There is still much to do to minimise visual discomfort, in both the laboratory and in the field.

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