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Lighting for work: a review of visual and biological effects

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With the detection in 2002 of a novel photoreceptor cell in the eye, the biological effects that light has can be better understood. From the research on the biological effects of lighting, it is evident that the rules governing the design of good and healthy lighting installations are, to a certain degree, different from the conventionally held rules. We demonstrate that it can be beneficial to be able to adapt both the level and the colour of the lighting. Not only the light on the visual task, but also that entering the eye determines the overall quality of lighting. In a working environment, not only are the advantages in terms of health and wellbeing important for the workers themselves, they also lead to better work performance, fewer errors, better safety, and lower absenteeism.

1. Introduction

The visual effects of lighting have been studied for more than 500 years. Leonardo da Vinci (1452–1519) described ideas about ‘street lighting’. Christiaan Huygens (1629–1695) formulated the wave theory of light, while Sir Isaac Newton (1642–1727) developed the corpuscular theory of light. Johann Wolfgang Goethe (1749–1832) analysed the colour effects and aspects of lighting.

With the introduction of gaslight and electric light in the early-to-mid 1800s, the study of visual lighting effects was directed more and more towards practical lighting application research.

As regards the mechanism of visual effects, as early as 1722 the Dutchman Antony van Leeuwenhoek noted the presence of ‘rod and cone cells’ in the retina. Their existence was confirmed as ‘the light sensitive photoreceptors’ in 1834 by the German Gottfried Treviranus. This discovery opened the way to the understanding of many of the visual lighting effects already described and to a more concrete investigation into the visual effects of lighting, the goal being to design more effective lighting installations.

For more than 150 years, scientists considered rods and cones to be the only photoreceptor cells in the eye. Seen in this historic context, it is sensational that in 2002 David Berson *et al.*[1] of Brown University (USA) detected a novel, third type of photoreceptor in the retina of mammals (in this study rats). This novel photoreceptor, a specific subtype of retinal ganglion cells, is a ‘missing link’ in describing the mechanism of biological effects as controlled by light and darkness. That lighting has important biological effects has been the subject of extensive studies in the biological and medical scientific world during the past 25 years. From this, we have learned that

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the effects of good lighting extend much further than visual effects only: the biological effects mean that good lighting has a positive influence on health, wellbeing, alertness, and even on sleep quality.[2–5] At the same time, it means that the lighting parameters with which good lighting can be described need to be revised.

This paper first reviews the mechanism of both visual and biological effects based on the three photoreceptors in the eye. Subsequent sections deal with lighting and visual effects, and lighting and biological effects. The first of these sections concludes with a summary of the 'vision-related' lighting quality aspects, while the second concludes with a discussion of 'health-related' lighting quality aspects.

2. Three types of photoreceptor cells in the eye

The photoreceptor cells in the retina of the eye, the cones and rods, regulate the visual effects. When light reaches these cells, a complex chemical reaction occurs. The chemical that is formed (activated rhodopsin) creates electrical impulses in the nerve that connects the photoreceptor cells with the back of the brain (visual cortex). In the visual cortex of the brain the electrical impulses are interpreted as 'vision'. Figure 1 shows the nerve connection between cones and rods in the eye and the visual cortex of the brain.

The rods operate in extremely low-level light situations (scotopic vision) and do not permit colour vision. The cone system is responsible for sharpness and detail and colour vision. For all indoor lighting situations, the cones are to a very large extent decisive.

The sensitivity of the cone and rod systems varies with varying wavelength of light, and thus with varying colour of light. This is illustrated in Figure 2, where the spectral eye sensitivity curves V_λ for the cone system and V'_λ for the rod system are given.

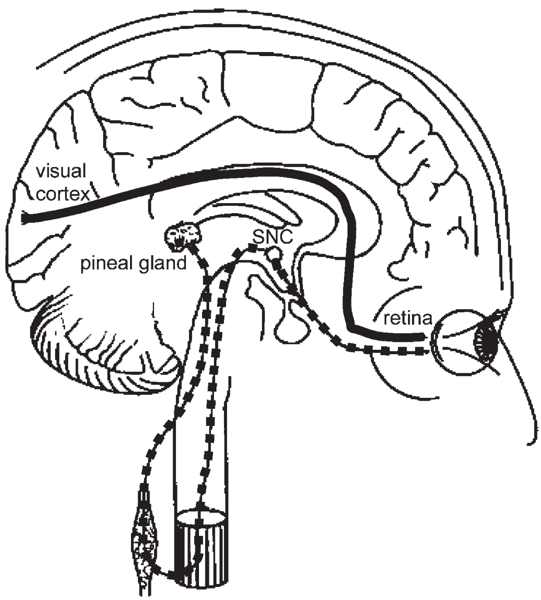

Figure 1 Visual and biological pathways in the brain: nerve connections between the retina of the eye, with its cones and rods, and the visual cortex on the one hand (continuous bold line) and between the retina, with the novel photoreceptor cell, and the suprachiasmatic nucleus (SNC) and the pineal gland (bold broken line)

The novel photoreceptor cell type in the retina of the eye detected by David Berson *et al.*[1] in 2002 regulates the biological effects. (Probably, the rods and cones do play a certain role in this respect as well.) When light reaches these cells, a complex chemical reaction occurs here involving the photo pigment melanopsin,[6] again producing electrical impulses. These cells have their 'own' nerve connections to, amongst others, locations in the brain called the suprachiasmatic nucleus (SNC), which is the biological clock of the brain, and the pineal gland. Figure 1 shows the nerve connection between the novel photoreceptor cells in the eye and these locations in the brain. The sensitivity of this novel photoreceptor cell also varies for different wavelengths of light. On the basis of the biological factor 'melatonin suppression', Brainard[7] was already able to determine the spectral 'biological action' curve. As will

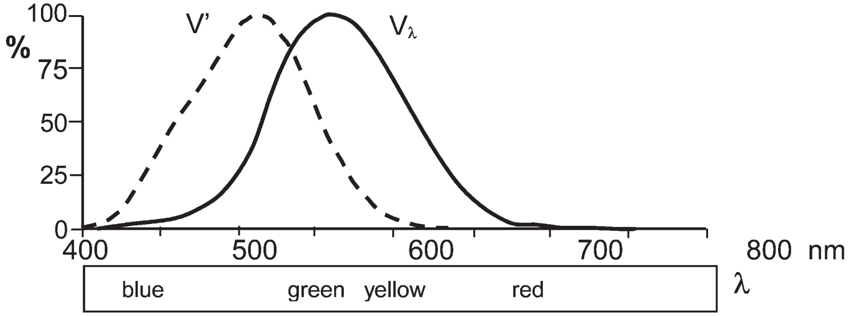

Figure 2 Spectral eye sensitivity curves, V_λ for the cone system (photopic vision: solid line) and V'_λ for the rod system (dotted line)

be discussed later in this article, one of the biological effects of light is the suppression of the hormone melatonin. Probably many other biological factors regulated by lighting will have an action spectrum similar to that determined on the basis of melatonin suppression. The spectral biological action curve is given in Figure 3, together with the visual eye sensitivity curve of cones.

By comparing the two curves it is immediately evident that the biological sensitivity for different wavelengths of light is quite different from the visual sensitivity. Where the maximum visual sensitivity lies in the yellow–green wavelength region, the maximum biological sensitivity lies in the blue region of the spectrum. These phenomena have an important meaning for the specification of healthy lighting.

3. Lighting and visual effects

3.1 Visual performance

The lighting quality should always be high enough to guarantee sufficient visual performance for the tasks concerned. However, a person's actual visual performance depends upon not only the quality of the lighting but also upon his or her own 'seeing abilities'. In this respect, age is an important criterion, since lighting requirements increase with age. Figure 4 gives the relative minimum amount of light required for reading a well-printed book, as a function of age. This research was carried out with test persons wearing, if required, the correct reading glasses. It is evident from this curve that the age effect is extremely severe. One of the many reasons for this age effect is the deterioration of the

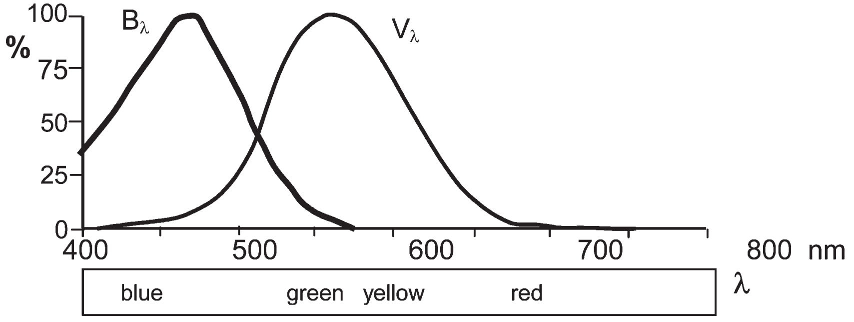

Figure 3 Spectral biological action curve B_λ (based on melatonin suppression), bold line, (source: Brainard[7]), and the visual eye sensitivity curve V_λ, thin line

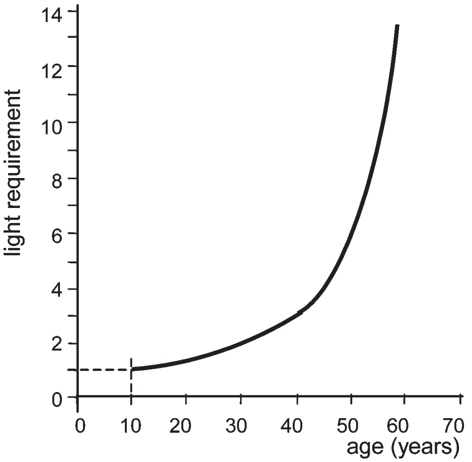

Figure 4 Relation between age and relative amount of light required for reading good print as a factor relative to the requirement of a 10-year-old person (source: Fortuin[8])

transmittance of the eyes' lenses: the lenses gradually turn yellowish (see Figure 5). This deterioration means that the ageing lens has a lower transmittance. It also means that less and less bluish light is transmitted. The ageing eye sees a less-blue world.

Figure 6 serves as an illustration of the many research results pertaining to the influence of lighting quantity on visual performance. It gives the relative visual performance as a function of lighting level for different visual task difficulties: one for a moderately difficult task (e.g. office work or general machine work in an industrial environment) and another for a difficult task (e.g. colour inspection work or fine assembly work). In the graph, the required lighting levels (EN) for industrial environments, as in many cases specified in the European Norm for the lighting of work places,[10] are indicated.

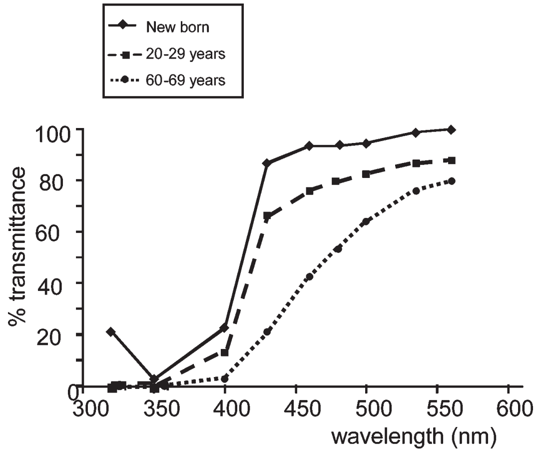

Figure 5 Lens transmittance for various age categories. Values are expressed as a percentage of the 560 nm point for the new born (source: adapted from Brainard *et al.*[9])

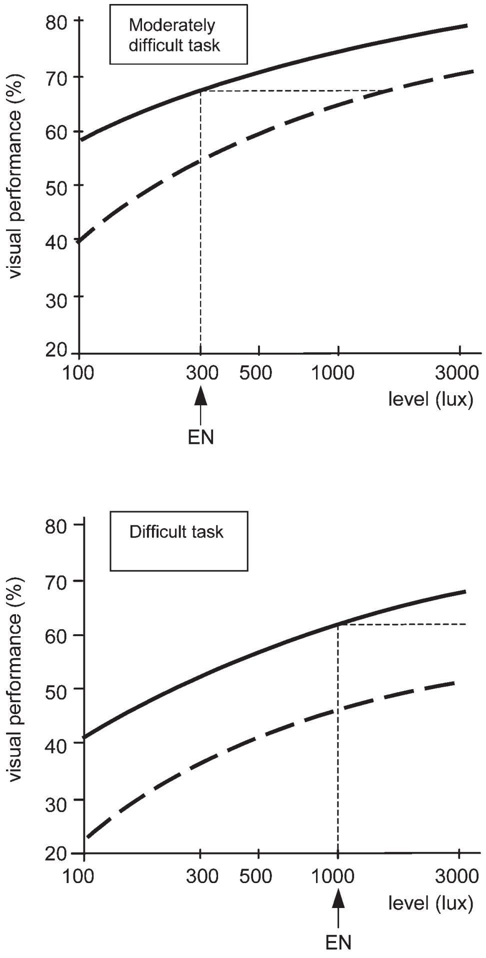

Figure 6 Relation between relative visual performance (in %) and lighting level (in lux). Continuous line: young people; broken line: older people (source: CIE[11]). EN: lighting levels specified in the European Norm

The graph shows that the requirements laid down in the European Norm are, in fact, well-suited to the younger persons. However, the visual performance of the older workers is considerably lower. Luckily, compensation with a higher lighting level is completely possible for the moderately difficult task. In practice, this calls for adaptable lighting on top of the lighting required by the 'EN Standard' for those moments that daylight is not sufficient to give the higher lighting levels needed for the older workers.

3.2 Visual environment

Besides its effect on visual performance, lighting can also have a powerful influence on atmosphere and the visual impression of the workplace. Properly designed, the overall working environment can have a stimulating effect on the people working within it.[12] Daylight contribution to the interior is another very important factor determining the quality of the working environment. Fortunately, in many cases daylight penetrates the building for at least several hours each day, considerably increasing the overall lighting levels. But daylight not only facilitates the visual performance of the visual task by contributing to the lighting on that task; because of its dynamic, varying character in both intensity and colour, it also contributes greatly, if properly controlled (e.g. by proper window and sun-shielding design), to a good working environment. The dynamic changes in daylight have a positive influence on mood and stimulation. An extensive study under office conditions has shown that people prefer artificial lighting in addition to the normal daylighting present in an office environment: average 800 lux on top of the prevailing daylight contribution.[13]

3.3 Vision-related quality aspects of lighting installations

Most national and international recommendations and standards specify lighting quality figures for the majority of the visual quality aspects mentioned earlier, and for a wide variety of interiors and activities. Table 1 lists the visual quality aspects together with the most important parameter for each aspect as used in the new European Norm for the lighting of workplaces.

As an illustration of what quality is required in different situations, Tables 2 and 3 give the required values specified in the European Norm for an office and for an industrial environment (the chemical, plastics and rubber industries). The values specified for the average illuminance are 'maintained illuminances': namely, values below which the average illuminance on the specified surface is

Table 1 Visual quality aspects of lighting installations with their quality parameters as specified in the European Norm for the lighting of workplaces[10]

Visual quality aspect	Quality parameter
Lighting level	Average illuminance level, E_{av}
Spatial distribution	Uniformity: E_{min}/E_{av} Glare restriction: UGR
Colour rendering	R_a

Table 2 Lighting requirements for offices (source: EN 12 464[10])

3 Ref. no.	Offices Type of interior, task or activity	E_{av} (lux)	UGR_L	R_a
3.1	Filing, copying, etc.	300	19	80
3.2	Writing, typing, reading, data processing	500	19	80
3.3	Technical drawing	750	16	80
3.4	CAD workstations	500	19	80
3.5	Conference and meeting rooms	500	19	80
3.6	Reception desk	300	22	80
3.7	Archives	200	25	80

Table 3 Lighting requirements for the chemical, plastics and rubber industries (source: EN 12 464[10])

2.5 Ref. no.	Chemical, plastics and rubber industry Type of interior, task or activity	E_{av}(lux)	UGR_L	R_a
2.5.1	Remotely-operated processing installations	50	—	20
2.5.2	Processing installations with limited manual intervention	150	28	40
2.5.3	Constantly-manned workplaces in processing installations	300	25	80
2.5.4	Precision measuring rooms, laboratories	500	19	80
2.5.5	Pharmaceutical production	500	22	80
2.5.6	Tyre production	500	22	80
2.5.7	Colour inspection	100	16	90
2.5.8	Cutting, finishing, inspection	750	19	80

never allowed to fall. The value specified for uniformity on the task is always the same: $E_{\min}/E_{av} \geq 0.7$.

These requirements are values that meet the needs of visual performance and visual comfort for workplaces for the majority of the workforce. However, as discussed, the age effect is so important that adaptable lighting on top of the ‘EN Standard lighting’ is needed for those moments when daylight is not sufficient to give the higher lighting levels that are required for the ageing eye.

4. Lighting and biological effects

The beneficial effect of (day)light has been well known since ancient times, an example being heliotherapy, or the treatment of disease by exposure of the body to the sun’s rays. Light therapy for dealing with health problems was popular until the 1930s, after which time the introduction of penicillin led to pharmaceuticals taking the leading role. Over the last 20–30 years, however, the appreciation of light as an important contributor to health and wellbeing has been revived, thanks to various findings in biological and medical research.

We normally think of the eye as an organ for vision, but due to the discovery of additional nerve connections from recently-detected novel photoreceptor cells in the eye to the brain, it is now understood how light also mediates and controls a large number of biochemical processes in the human body. The most important findings are related to the control of the biological clock and to the regulation of some important hormones through regular light–dark rhythms. This in turn means that lighting has a large influence on health, wellbeing and alertness.

4.1 Light and body rhythms

Light sends signals via the novel photoreceptor cells and a separate nerve system to our biological clock, which in turn regulates the circadian (daily) and circannual (seasonal) rhythms of a large variety of bodily processes. Figure 7 illustrates some typical rhythms in human beings. The figure shows only a few examples: body temperature and the hormones cortisol and melatonin. The variation in body temperature represents in absolute values for a healthy person some 0.4°C.

The hormones cortisol (‘stress hormone’) and melatonin (‘sleep hormone’) play an important role in governing alertness and sleep. Cortisol increases blood sugar to give the body energy and enhances the immune system. However, when cortisol levels are too high over a too-long period, the system becomes exhausted and inefficient. Cortisol levels increase in the morning and prepare the body for the coming day’s activity. They remain at a sufficiently high level over the course of the bright day, falling finally to a minimum at midnight. The level of the sleep hormone melatonin drops in the morning, reducing sleepiness. It normally rises again when it becomes dark, permitting healthy sleep

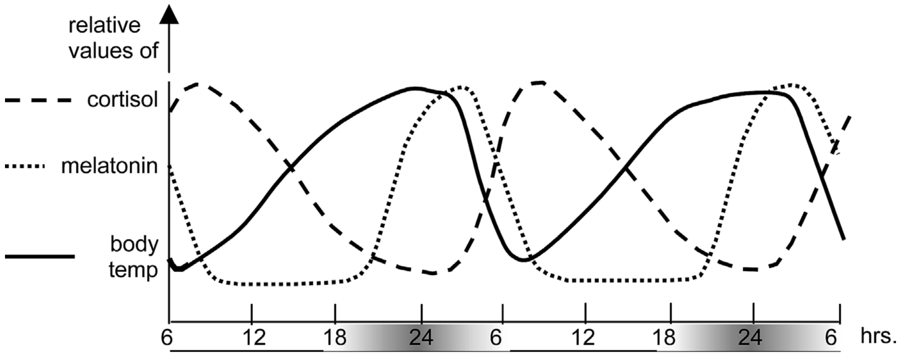

Figure 7 Double plot (2 × 24 h) of typical daily rhythms, between their relative minimum and maximum values, of body temperature, melatonin, and cortisol in humans for a natural 24-h light/dark cycle

(also because cortisol is then at its minimum level). For good health, it is of importance that these rhythms are not disrupted too much. In the case of a disruption of the rhythm, exposure to bright light in the morning will help to restore the normal rhythm.

In a natural setting, light, especially morning light, synchronizes the internal body clock to the earth's 24-h light–dark rotational cycle. Without the regular 24-h light–dark cycle, the internal clock would be free-running with, for humans, an average period of about 24 h and 15–30 min. This would, as a consequence, produce ever-greater day-to-day deviations in our body temperature, cortisol and melatonin levels from those set by the environmental clock time.[14] This desynchronization in the absence of the 'normal' light–dark rhythm would result in an incorrect rhythm of alertness and sleepiness, ultimately leading to alertness during the dark hours and sleepiness during the bright hours. The same symptoms, in fact and for the same reason, that are associated with jet lag after travelling over several time zones.[15] Rotating shift workers also experience the same symptoms for a couple of days after each shift change, again for the same reason.[16]

4.2 Lighting, alertness, mood and stress

A wealth of research projects that compare the effects of health, wellbeing and alertness as a result of people working under different lighting conditions have already been carried out. In this article we will discuss only a limited but typical number of these.

Küller and Wetterberg[17] studied the brainwave pattern (EEG) of people in a laboratory made to look like an office environment, once with a relatively high lighting level (1700 lux) and once with a relatively low lighting level (450 lux). The composition of the EEGs exhibit a pronounced difference: the higher lighting level results in fewer delta waves (the delta activity of an EEG being an indicator of sleepiness), meaning that bright light has an alerting influence on the central nervous system (see Figure 8).

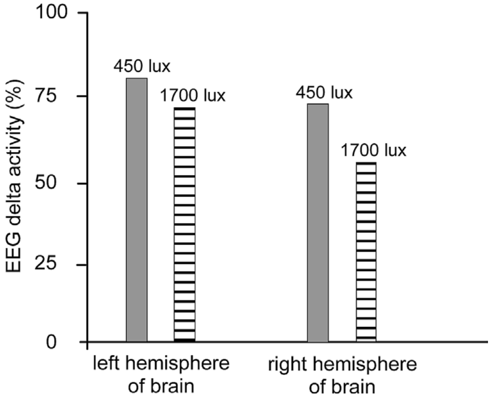

Figure 8 Delta activity in the EEG during the afternoon of office workers for uniform lighting levels on the desks of 450 lux and 1700 lux (source: Küller and Wetterberg[17])

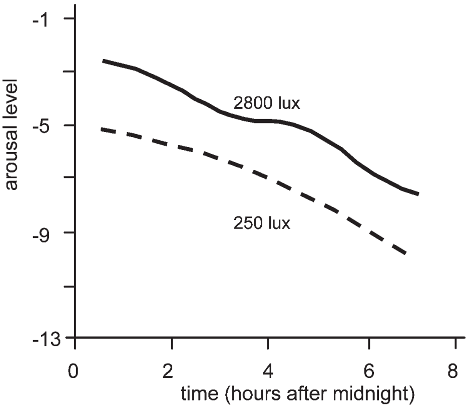

Figure 9 Alertness and mood expressed as arousal level (on a −24 to +24 scale of Mehrabian and Russell) for uniform lighting levels on the desks of 250 lux and 2800 lux, as a function of working hours after midnight (source: Boyce *et al.*[18])

Many investigations into the effects of light on alertness and mood have been carried out under night-shift conditions, because here the effects to be expected would be strongest. Figure 9 shows the effect of two lighting regimes on arousal as a function of time at work for shift-workers.[15] A decline in arousal over the night occurs for both regimes, but the high-light regime always results in a significantly increased arousal level and thus better alertness and mood.

Other studies show that the use of higher lighting levels to cope with fatigue indeed results in the subjects staying alert longer.[19–21]

Studies of stress levels and complaints in people working indoors have been made by comparing a group of people working solely under artificial light with a group working under a combination of artificial light and daylight.[22] As can be seen from Figure 10, in January, when daylight penetration is not sufficient to make a substantial contribution to the lighting level, there is hardly any difference between the two groups. But in May, when daylight really contributes, the group benefiting from daylight has a considerably lower stress complaint level. Another study shows that bright artificial light in interiors in winter has a positive effect on mood and vitality.[23]

Some people experience headaches because of the light ripple caused by the 50 Hz power supply of fluorescent lamps operated on magnetic ballasts. Fluorescent lamps running on modern, high-frequency electronic ballasts operate at around 30 kHz and thus do not exhibit this flicker or ripple phenomenon. In a comparison, it has been found that the occurrence of headache is, indeed, significantly lower when electronic ballasts are used.[24] Küller and Laike[25] measured the EEG of persons working in an office

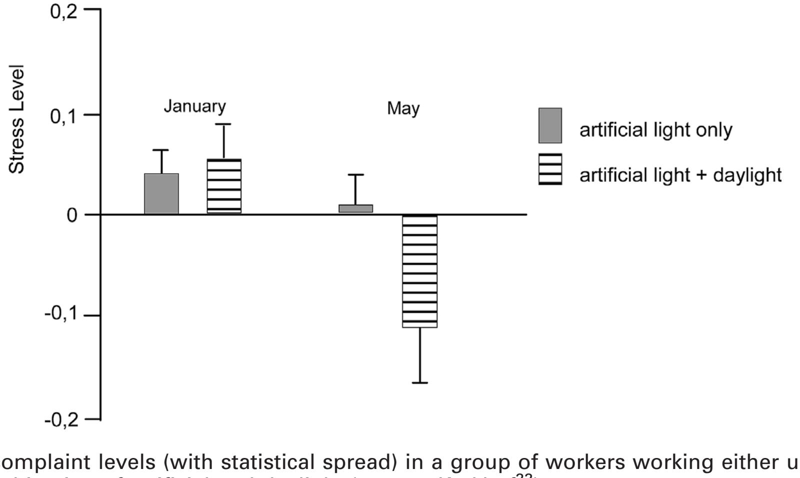

Figure 10 Stress complaint levels (with statistical spread) in a group of workers working either under artificial light only or under a combination of artificial and daylight (source: Kerkhof[22])

environment under respectively magnetic (50 Hz) and high-frequency fluorescent lighting. At the same time, they also measured the speed and errors made in a proof-reading task. Figure 11 shows that the reciprocal value of the alpha activity of the EEG, and therefore the brain arousal ('stress'), is higher with the 50 Hz operated lighting. The working speed is slightly higher, but the errors are dramatically higher (more than double). The combined effect means that it is wise, from both the wellbeing and productivity points of view, to use high-frequency fluorescent lighting instead of magnetic 50 Hz lighting to limit brain arousal or stress.

4.3 Health-related quality aspects of lighting installations

The visual-quality aspects of lighting installations as listed in an earlier section i.e., lighting level, spatial distribution of light and colour rendering, have to be refined and extended if we want to arrive at truly 'good and healthy' lighting installations.

The biological effect of light is not steered directly by the illuminance on the working plane, but by light entering the eye. Studies are under way to see how this difference between 'visual lighting level on the task' and 'biological lighting levels' can be accounted for.[26] Very recent research indicates that light on the upper and lower part of the retina has different importance as far as the resulting biological effect is concerned.[27] This suggests that also the spatial distribution of light is important from a 'health' point of view. As has been illustrated, especially because of the effects due to ageing eyes, the lighting level has to be adaptable.

Daylight by its nature is dynamic in its intensity. There are indications that a variable lighting condition has a positive effect on the activation state of people in an office environment.[28] Where the benefits of the dynamics of daylight intensity are not sufficiently available, dynamic artificial light can be advantageous.

Two complete new aspects relate to the timing and duration of the lighting. Visually, of course, light is only needed when and for as long as one 'views'. Biologically, however, the time when the light (or darkness) is received and its duration plays an essential role, as is evident from the rhythm graph of Figure 7.

We have always realized that the colour of light itself has an emotional meaning, and is therefore important for the atmosphere of a space. But we now also understand that the spectrum and thus the colour of light has an important biological meaning. As was shown

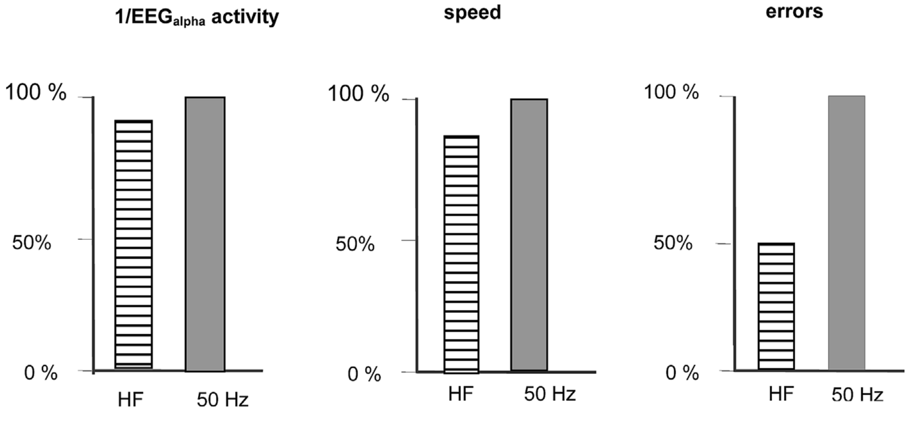

Figure 11 Brain arousal measured as the reciprocal value of the alpha activity of EEGs in persons in offices under 50 Hz and under high-frequency HF (30 kHz) fluorescent lighting. The working speed and errors of a proof-reading task are also given (graph adapted from: Küller and Laike[25], relative values). Subject group: high flicker sensitivity

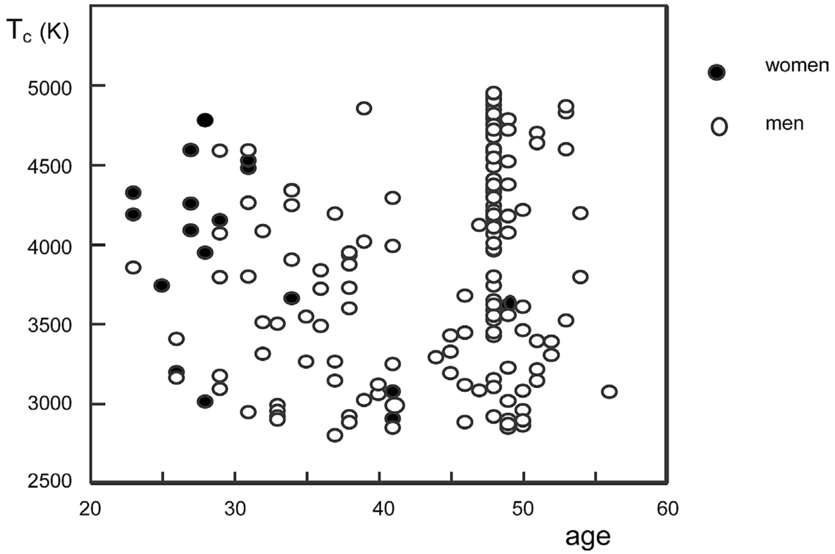

Figure 12 Colour preference of artificial light in an office with (daylight) windows, expressed as correlated colour temperature of the light, T_c, for different ages. Each symbol represents the average preference of T_c over the whole day as set by each test person (source: Tenner[29]).

in the section on the novel photoreceptor cell, bluish, cool light has biologically a larger effect than warmer coloured reddish light (Figure 3). Thus bluish morning light has biologically an activating (alerting) effect, while the red sky that we see more often in the early evening, has a relaxing effect. In a working environment, both activating and relaxing moments are required. The colour and lighting level of the artificial lighting together may help to create these moments. Studies in an office environment where the preferred colour temperature of the artificial lighting could be remotely set by test persons working a whole day in the office have shown that there is no trend in preference between individuals in this respect: everyone has their own personal preference (Figure 12).

Table 4 Vision-and health-related quality aspects of lighting installations

Lighting quality aspects Vision related	Health related
Lighting level on the task	lighting level in the eye
Spatial distribution	spatial distribution
Colour rendering	(adaptable) colour appearance
	timing
	duration

Table 4 summarizes the vision- (from Table 1) and health-related lighting quality aspects that together determine ‘good and healthy’ lighting.

5. Conclusion

Due to the recent discovery of a novel photoreceptor in the eye, we are now much better able to understand why the benefits of good lighting at work, taking into account both the visual effects and the biological effects (namely, health, wellbeing and alertness), are so important. Apart from the health and wellbeing advantages for the workers themselves, good lighting also leads to better work performance (speed), fewer errors and rejects, better safety, fewer accidents, and lower absenteeism. The overall effect of all this is: better productivity. For an industrial environment (moderately difficult visual task in the

Table 5 Increase in productivity in the metal-working industry with a moderately difficult visual task as the combined effect of increased work performance, errors/rejects reduction and accident reduction (source: van Bommel *et al.*[30])

Improvement of lighting level	Productivity increase
From 300 to 500 lux	8%
From 300 to 2000 lux	20%

metal working industry), we derived from a detailed literature survey dealt with in detail in a separate publication[30] the possible resulting total productivity increase as a result of improved lighting level. Table 5 provides a summary of the results.

To confirm the results, we are carrying out real-life productivity investigations in a number of industrial environments. A first report will be presented at the Licht 2004 Conference in Dortmund, Germany.[31] Realizing the importance of the biological component in the productivity increase, we believe that similar figures can also be obtained in an office environment. By putting our advice for flexible and adaptable lighting levels and colours into practice, such productivity advantages will become even more impressive.

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Discussion

Comment 1 on 'Lighting for work: a review of visual and biological effects' by WJM van Bommel and GJ van den Beld

***PT Stone (47 Loughborough Road, Quorn, Leicestershire,** UK)*

The authors have presented a most comprehensive and up-to-date overview of those aspects of lighting which are thought to affect biological, visual and performance changes in human behaviour. My comments are directed in the first case to the biological aspects of the paper.

I think it is necessary to question how well substantiated some of the biological findings are before accepting them as reliable data for application since in some instances, they result from a limited number of experiments. There is also the question of making inferences from experimental work as for instance in the statement that 'bluish morning light biologically has an activating (alerting) effect', which is speculative inference. Likewise, while 'the red sky that we see more often in the early evening has a relaxing effect' is possibly true for many people, it is anecdotal and not established science. Whether artificial light could or should create these effects in the work place poses major questions, as indeed does the notion that bodily rhythms could be stimulated with appropriate light sources to keep people more alert on night shifts.

The paper reports the finding of a novel third photoreceptor in rats and one naturally wishes to know whether there is a similar receptor in the human retina. Does it have the same structural characteristics as a rod or cone cell or some unique morphology? What is the response to light intensity and does the receptor respond in the photopic, mesopic or scotopic range?

Figure 3 shows a spectral response curve for the suppression of melatonin in humans which has quite a wide sensitivity to wavelength. Is this intended to represent the action spectrum of the 'new' photoreceptor and if so, why should a new photoreceptor be required when there is a significant spectral power range to stimulate receptors which already exist? My general point is that whilst biological science is very interesting it is insufficiently developed for general application to lighting design.

My second comment is related to a visual aspect of interior lighting which is referred to by the the authors and I think they come to a really important feature here. They state that 'dynamic artificial light can be advantageous'. This is a concept that has been very neglected although the technology exists for the exploration and realization of successful designs. An early pilot experiment by Aldworth and Bridgers[1] gives a lead which shows considerable promise, indicating that dynamic lighting (in the experiment) tended to be favoured, but further work on this topic has not been followed up in any major way. Variability in intensity and distribution of the lights in an interior could be important, especially in a workplace, where people are in a static position, or in a hospital ward, where patients can be confined for long periods. Where artificial lighting is required throughout the day, the constancy of the light can generate bland, monotonous and boring visual environments and such conditions should be more amenable to more dynamic design. My main point here is that there is still much adventurous and quality research and application to be done into the visual aspect of lighting design.

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Comment 2 on 'Lighting for work: a review of visual and biological effects' by WJM van Bommel and GJ van den Beld

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These are exciting times for lighting researchers; a new vista opens before us, moving beyond stale questions about discomfort glare prediction and visual performance at threshold. We know enough to state authoritatively that the intensity, timing, duration, spectrum and pattern of light exposure influence human physiology and behaviour, but we cannot state with precision what conditions (or combination of conditions) will lead to optimal health and well-being.[1] Answering the fundamental questions will require true interdisciplinary collaboration among physiology, psychology, physics, and medicine. Answering applied questions concerning how to achieve the desired conditions in real spaces using practical equipment will add engineering, architecture, lighting design, industrial design and human factors/ergonomics to the mix of expertise.

We are a long way from having final answers—further, I think, than the authors imply. For example, there are competing spectral response curves for melatonin suppression in addition to Brainard's result.[2,3] One study has suggested that there might be an opponent process in which the simultaneous presence of long-wavelength radiation might counteract the melatonin-suppressing effect of short-wavelength radiation.[4] Different recommendations for the characteristics of light sources for circadian phase regulation will emerge depending on how this research develops in the coming years, and this is but one example.

More generally, we should be cautious about recasting our recommendations to suit circadian physiology based principally on studies of melatonin suppression. Although melatonin physiology has received the lion's share of research attention, it is not the only process influenced by patterns of light and dark exposure. We have much to learn about other neural and hormonal mechanisms that respond to light and dark.

Nonetheless, it is time to raise awareness of the dramatic research findings emerging from photobiology, as these authors have done. The shift in emphasis from threshold visibility to integrated models of lighting quality is recent,[5,6] and it will take time and consideration to determine the best way to further integrate health and wellbeing goals into lighting practice. Both Lynes and Stone, commenting on a paper by Rea, Figueiro and Bullough in 2002,[7] rightly commented that lighting recommendations based on circadian photobiology will succeed only to the extent that they are integrated with recommendations derived from other processes such as vision and perception. van Bommel and van den Beld have here made the point that there may be differences in the rules derived from various approaches. I would add that the energy-use implications of changes to lighting practice also merit consideration. Recommendations will need to resolve those differences, or provide guidance as to the contexts in which one rule or another should take precedence. There is much to learn, and much to debate, as we move with deliberation to revolutionize lighting practice.

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Authors' response to PT Stone and JA Veitch

WJM van Bommel and GJ van den Beld

We want to thank Mr Stone and Dr Veitch for their interesting comments.

Mr Stone's main point is that 'biological science is very interesting, but insufficiently developed for general application to lighting design'. Dr Veitch expresses her opinion that 'we are a long way from final answers', but she is clearly more positive with her statement: 'dramatic research findings emerging from photobiology'. While, of course, we accept that still much has to be learnt, we are also convinced that already so much is known that we can, or better, should start carefully bringing some of the research results into the practice of lighting design. The real problem is twofold, one: the awareness in the lighting community is still too limited, and two: as Dr Veitch states, 'true interdisciplinary collaboration among the worlds of physiology, psychology, physics, medicine', and we strongly urge that the addition of 'lighting practice', is urgently needed. In this respect the initiative of CIE in organizing an Expert Symposium on Light and Health, where experts from these disciplines were invited to participate, is important (Vienna, September 2004).

As Mr Stone comments, our statement of 'bluish morning light acting activating and red evening sky relaxing', may have some speculation in it, but becomes even more convincing after studying recent publications of Scheer[1] and of Leproult,[2] where it is shown that white morning light has a direct effect on cortisol levels and on alertness, and also when one accepts that evolution has played a major role in determining human bodily mechanisms.

Regarding Mr Stone's question about the novel third photoreceptor: the rods and cones do not give a fit with the 'biological' action spectrum (melatonin suppression), thus there must be novel photopigment(s) involved. It has been shown that in mammals melanopsin indeed plays such role. Provencio[3] also found melanopsin in the human eye. Chiquet[4] found that the width of the action spectrum for human melatonin suppression is wider than would be expected if only a single photopigment were active. The novel photoreceptor probably works in combination with the 'vision' photoreceptors resulting in this wider action spectrum. We very much agree with Mr Stone that the concept of dynamic artificial lighting can be advantageous. It is interesting to note that photobiologically a step change (block function) is more effective than a gradual change Hut.[5]

The correct comment of Dr Veitch that there are competing spectral response curves for melatonin suppression does not imply that the differences are large. Five recent action spectra developed in separate studies (involving humans and animals) found a common 446 nm–484 nm region of peak sensitivity.[6]

We agree with Dr Veitch that energy use also merits consideration. Also therefore it is so important to understand that the biological action spectra are different from the visual action spectra. By using light sources with suitable spectra the same bodily effect can be obtained at lower lighting levels. The question to be answered is how acceptable such spectra are visually for, for example, people at work. These phenomena will also have to be taken into account in the development of new light sources.

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