LIGHTING FOR WORK: VISUAL AND BIOLOGICAL EFFECTS

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CONTENTS

SUMMARY

With the detection in 2002 of a novel photoreceptor cell in the eye, the biological effects that light has on human beings can be better understood. The spectral sensitivity of the novel cell type has in the meantime been studied and shows that bluish light has biologically a larger activating effect than does reddish light.

A large number of research projects that compare the effects on health, well-being and alertness as a result of people working under different lighting conditions have been carried out. The results, as summarised in this article, show that good lighting indeed has important beneficial effects, not only visually but also biologically. 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 have both the level and the colour of the lighting adaptable. 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 well-being important for the workers themselves, they also lead to better work performance, fewer errors, better safety, and lower absenteeism. An example from an industrial environment demonstrates that by changing the lighting from 300 to 500 lux may easily increase the overall productivity by 8 per cent.

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 the Brown University (USA) detected a novel, third type of photoreceptor in the retina of mammals. This novel photoreceptor 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 twenty-five years. From this, we have learned that 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, well-being, alertness, and even on sleep quality [2], [3], [4]. At the same time, it means that the lighting parameters with which good lighting can be described need to be revised.

This article first describes 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.

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.

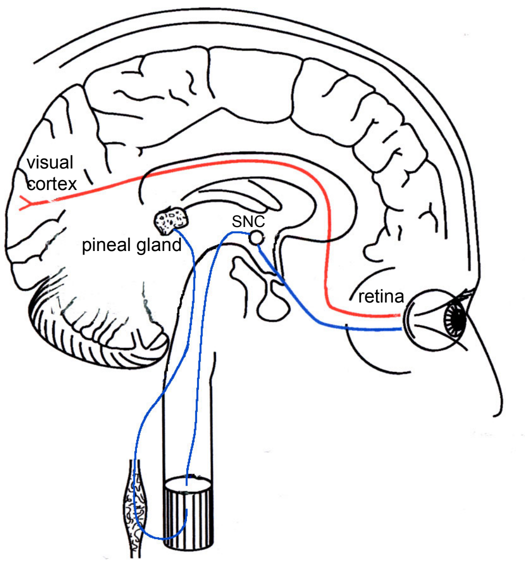

Fig. 1 Visual and biological pathways in the brain: nerve connections between the retina of the eye, with its cones and rods, and the visual cortex on the one hand (in red) and between the retina, with the novel photoreceptor cell, and the suprachiasmatic nucleus (SNC) and the pineal gland (in blue).

The rods operate in extremely low-level light situations (scotopic vision) and do not permit of 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. The V_λ curve for the cone system is the basis for all lighting units such as lumen, lux and candela. It is called the photopic system. As can be seen from the V_λ curve, the eye is not very sensitive to extreme blue and extreme red light, and has its maximum sensitivity for green-yellow light.

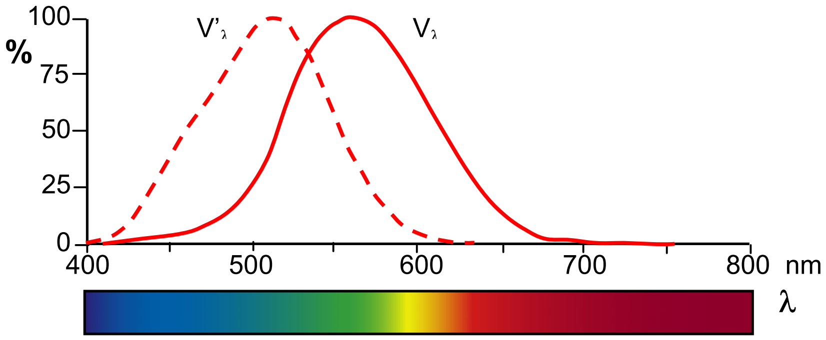

Fig. 2 Spectral eye sensitivity curves, V_λ for the cone system (photopic vision: solid line) and V'_λ for the rod system (dotted line).

It should be noted that different light colours can be obtained by different mixtures of wavelengths. White light consists of such a mixture. It is evident that the (visual) efficacy of a light source is very much determined by the spectral eye sensitivity and the wavelengths that are incorporated in its light.

The novel photoreceptor cell type in the retina of the eye detected by David Berson et al. [1] in 2002 regulates the biological effects[1]. When light reaches these cells, a complex chemical reaction occurs (here involving the photo pigment melanopsin [5]), 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, of course, for different wavelengths of light, and thus for different colours of light. On the basis of the biological factor "melatonin suppression", Brainard [6] was already able to determine the spectral "biological action" curve[2]. This curve is given in Figure 3, together with the visual eye sensitivity curve of cones.

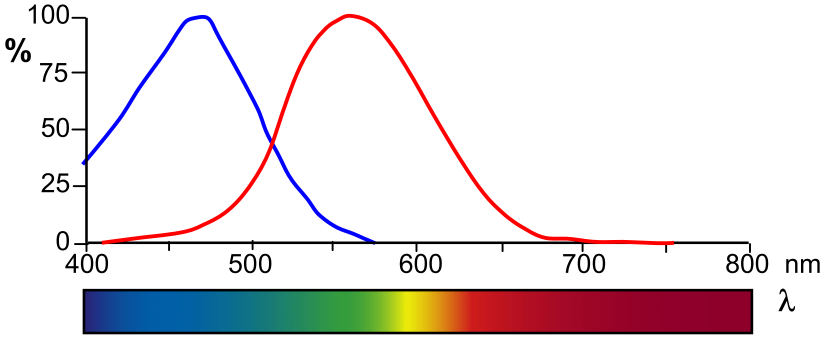

Fig. 3 Spectral biological action curve (based on melatonin suppression), in blue, (source: Brainard [6]), and the visual eye sensitivity curve, in red.

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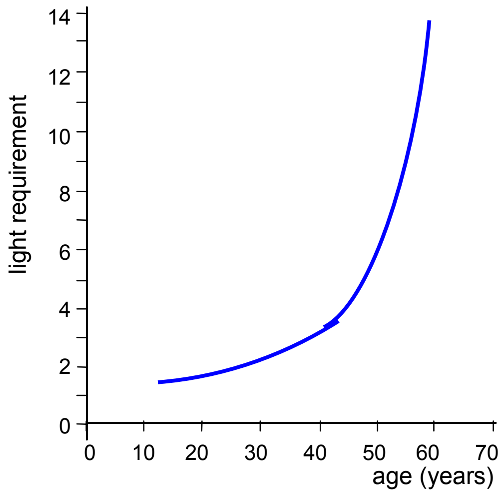
[1] Probably, the rods and cones do play a certain role in this respect as well.
[2] As will be discussed further on in this article, one of the biological effects of light is the suppression of the hormone melatonin. Probably many other biological factors regulated by lighting will have an action spectrum similar to that determined on the basis of melatonin suppression.

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.

LIGHTING AND VISUAL EFFECTS

Visual performance

Lighting for work covers a wide range of different working interiors and tasks: from offices and small workshops to huge factory halls, and from reading, writing and PC working tasks to fine precision work or heavy industrial tasks.
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 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 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.



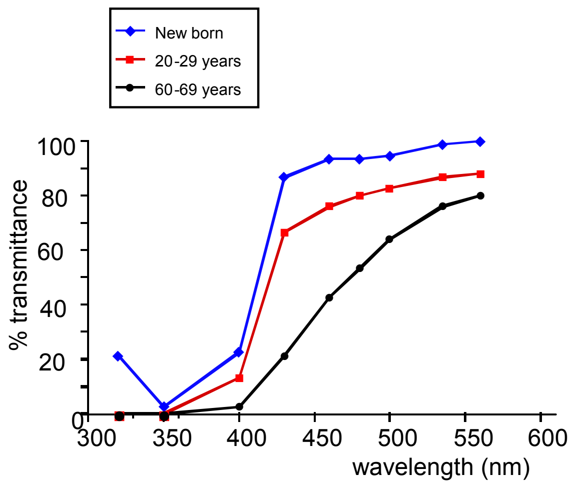


Fig. 4 Relation between age and relative amount of light required for reading good print (source: Fortuin [7]).

Fig. 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. [8]).

Figure 6 serves as an illustration of the many research results pertaining to the influence of lighting quality 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). All tasks show a clear increase in visual performance with increased lighting quality – in this example the lighting level. 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 [9], are indicated.

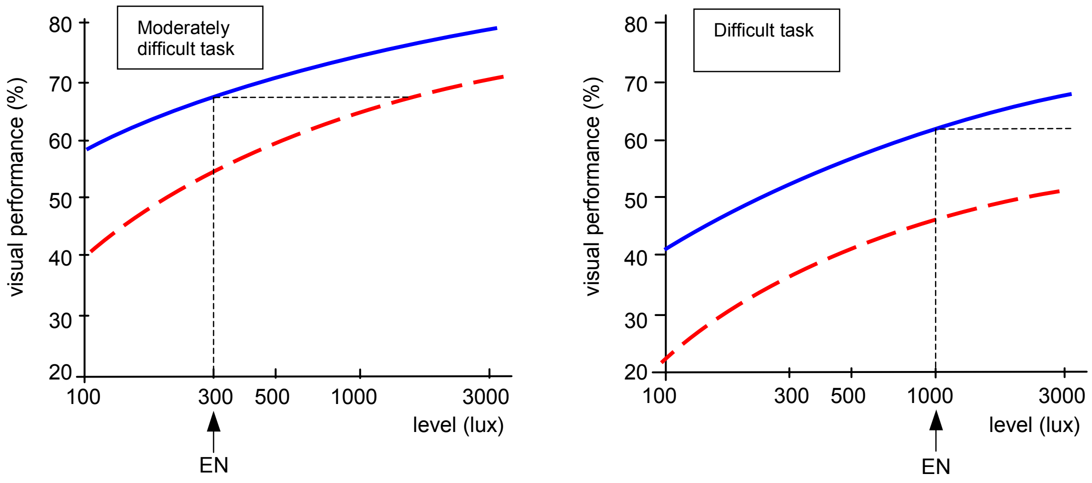


Fig. 6 Relation between relative visual performance (in %) and lighting level (in lux). Continuous blue line: young persons; broken red line: older persons (source: CIE [10]). EN: lighting levels specified in the European Norm.

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.

Of course, an improvement in visual performance yields, in its turn, an improvement in sustained work performance, reflected in a higher output and in a lower number of errors. The extent to which good-quality lighting enhances work performance depends, of course, on the visual component of the task. A task with an important visual component will benefit more from good seeing conditions than a task with a less important visual component.

Visual environment
Besides its effect on visual performance, lighting also can have a powerful influence on atmosphere and the visual impression gained of the workplace. Properly designed, the overall working environment can have a stimulating effect on the people working within it [12]. Today, a lot of emphasis is placed on the layout and interior design of the workplace. Good lighting can strengthen the interior design, but poorly-designed lighting can diminish or even "destroy" the effect of the interior design.
One aspect that is important in this respect is a controlled brightness of the surfaces that form the physical limits of the space, such as walls, floor and ceiling. The brightnesses of these surfaces determine to a large extent how the total space is experienced. Another factor is a proper limitation of glare and undesirable light reflections. Glare is the sensation produced by brightness levels within the visual field that are considerably greater than the brightness to which the eyes are adapted. Owing to limitations in the adaptation properties of the eye, abrupt changes in

brightness may lead to reduced visual performance and to visual stress and discomfort.
The colour properties of the light should also receive considerable attention. The lighting should permit the “real” colours to be seen. Proper colour rendering of the human skin is especially important, since lighting that makes the skin look pale and unhealthy often leads to complaints. Also, the colour appearance of the light itself plays a role in providing the space with an atmosphere. It may even have an emotional influence. For example, a somewhat bluish-white light gives a cool impression that is often experienced as businesslike, while reddish-white light gives a warm impression that may be experienced as cosy and relaxing.
Finally, 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].

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 above, 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 European Norm for the lighting of workplaces.
It should be noted that the colour appearance of the light itself is not specified in the European Norm. The reason for this is that so far the colour appearance is seen as a matter of psychology and aesthetics, and of what is considered to be natural.

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 1 Visual quality aspects of lighting installations with their quality parameters as specified in the European Norm for the lighting of workplaces [9].

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)[3]. 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 above, the age effect is so

[3] The values specified for the average illuminance are “maintained illuminances”: viz. values below which the average illuminance on the specified surface is never allowed to fall. The value specified for uniformity on the task is always the same: $E_{min} / E_{av} \geq 0.7$.

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.

3	**Offices**				
Ref. no.	**Type of interior, task or activity**	$\bar{E}_m$	UGR_L	R_a	**Remarks**
3.1	Filing, copying, etc.	300	19	80	
3.2	Writing, typing, reading, data processing	500	19	80	DSE-work: see clause 4.11.
3.3	Technical drawing	750	16	80	
3.4	CAD workstations	500	19	80	DSE-work: see clause 4.11.
3.5	Conference and meeting rooms	500	19	80	Lighting should be controllable.
3.6	Reception desk	300	22	80	
3.7	Archives	200	25	80	

Table 2 Lighting requirements for offices (source: EN 12 464 [9]).

2.5	**Chemical, plastics and rubber industry**				
Ref. no.	**Type of interior, task or activity**	$\bar{E}_m$	UGR_L	R_a	**Remarks**
2.5.1	Remotely-operated processing installations	50	-	20	Safety colours shall be recognisable
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	1000	16	90	$T_{CP} \geq 4000$ K.
2.5.8	Cutting, finishing, inspection	750	19	80	

Table 3 Lighting requirements for the chemical, plastics and rubber industries (source: EN 12 464 [9]).

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 to 30 years, however, the appreciation of light as an important contributor to health and well-being 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, well-being and alertness.

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, alertness, and the hormones cortisol and melatonin

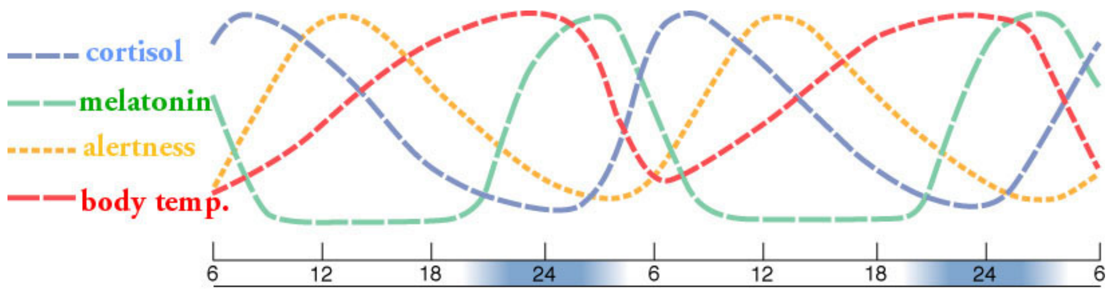


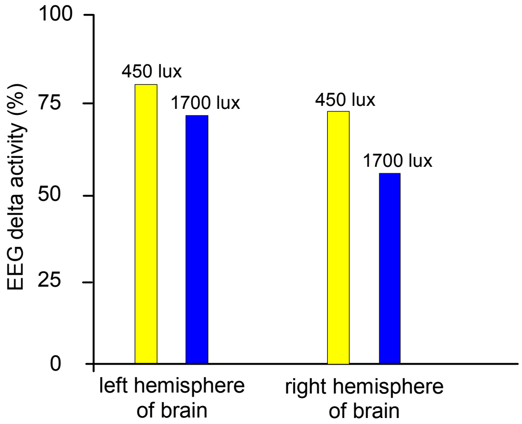
Fig. 7 Double plot (2 x 24 hours.) of typical daily rhythms of body temperature, melatonin, cortisol, and alertness in humans for a natural 24-hour light/dark cycle.

The hormones cortisol ("stress hormone") and melatonin ("sleep hormone") play an important role in governing alertness and sleep. Cortisol, amongst others, 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 (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 case of a disruption of the rhythm, bright light in the morning helps restoring the normal rhythm.
In a natural setting, light, especially morning light, synchronises the internal body clock to the earth's 24-hour light-dark rotational cycle. Without the regular 24-hour light-dark cycle, the internal clock would be free-running with, for humans, an average period of about 24 hours and 15 to 30 minutes. 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 deharmonisation in the absence of the "normal" light-dark rhythm would result in a wrong 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].

Lighting, health, well-being, and alertness

A wealth of research projects that compare the effects of health, well-being 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 them these.

Küller and Wetterberg [17] studied the brain-wave 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).
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.



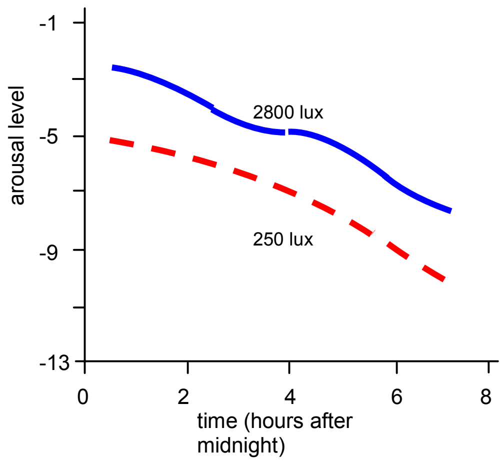


Fig. 8 Delta activity in the EEG of office workers under lighting levels of 450 lux and 1700 lux (source: Küller and Wetterberg [17]).

Fig. 9 Alertness and mood expressed as arousal level for lighting levels of 250 lux and 2800 lux, as a function of working hours after midnight (source: Boyce et al. [18]).

Other studies show that the use of higher lighting levels to cope with fatigue results in the subjects indeed staying alert longer [19], [20], [21].
Studies of stress levels and complaints in people working indoors have been made by comparing a group of people working under artificial light only 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].

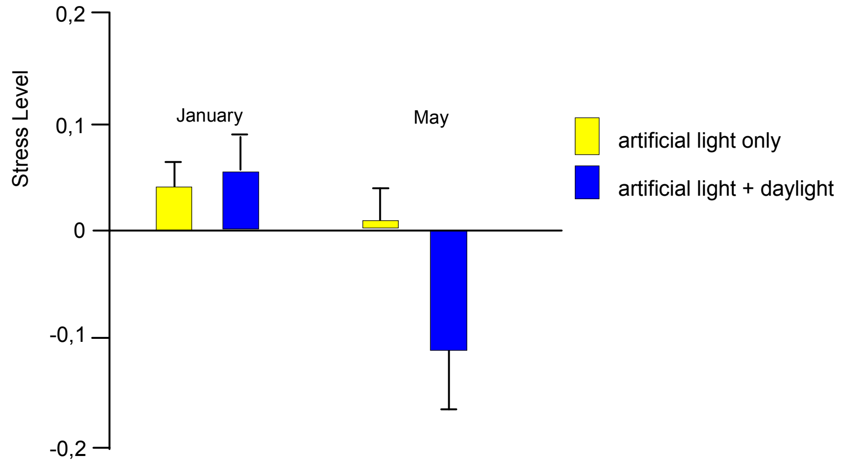


Fig. 10 Stress complaint levels (with statistical spread) in a group of workers working either under artificial light only or under a combination of artificial and daylight (source: Kerkhof [23]).

Some, but few 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 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 well-being and productivity points of view, to use high-frequency fluorescent lighting instead of magnetic 50 Hz lighting to limit brain arousal or stress.

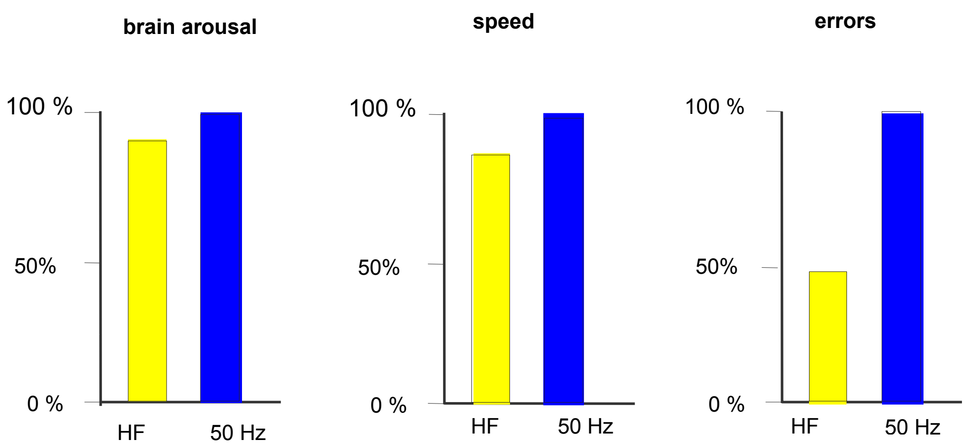


Fig. 11 Brain arousal measured as the reciprocal value of the alpha activity of EEGs in persons in offices under 50 Hz and under high-frequency HF (30 kHz) fluorescent lighting. The working speed and errors of a proof-reading task are also given (graph adapted from: Küller and Laike [25]). Subject group: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

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][4].

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 realised 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 in the section on the novel photoreceptor cell, bluish, cool light has biologically a larger effect than warmer coloured reddish light (Figure 3). The daylight situations of the photographs shown in Figure 12 produce not only a different emotional feeling but also have a different biological effect.

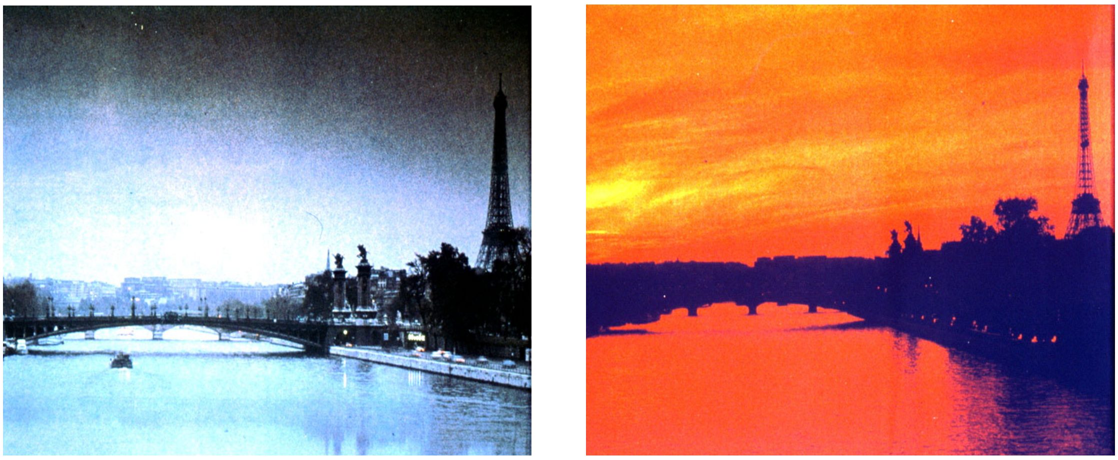


Fig. 12 Ambient colour early in the morning and early in the evening in Paris.

The bluish morning light has biologically an activating (alerting) effect, while the red sky 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

[4] 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.

artificial lighting together may help to create these moments. Studies on the preferred colour of light in an office environment have shown that there is no trend in preference between individuals in this respect: everyone has their own personal preference (Figure 13).

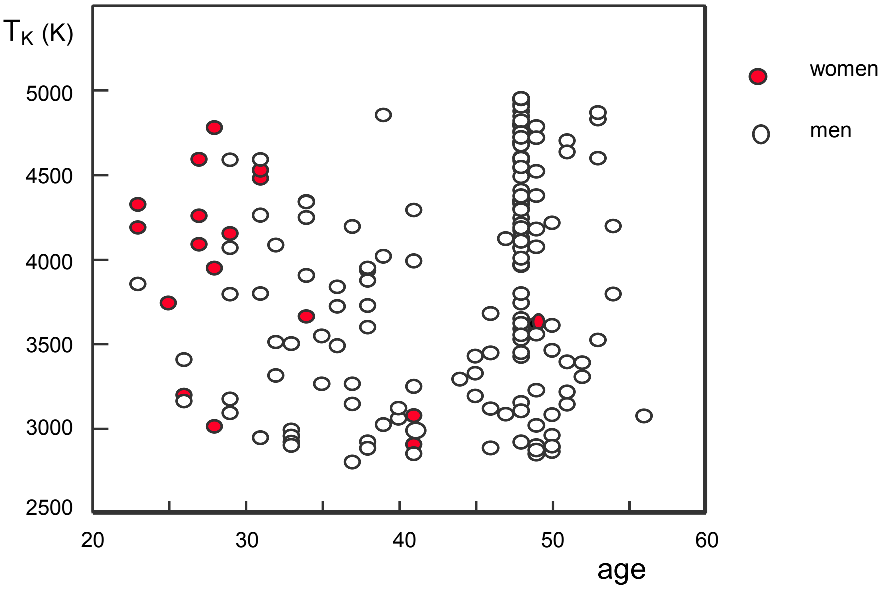


Fig. 13 Colour preference of artificial light in an office with (daylight) windows, expressed as correlated colour temperature of the light T_k for different ages and for men and women (source: Tenner [29]).

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

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

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

CONCLUSION

Thanks 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 (viz. health, well-being and alertness), are so important. Apart from the health and well-being 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), we investigated the possible resulting total productivity increase as a result of improved lighting level [29]. Table 5 provides a summary of the results.

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

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]).

To confirm the results, we are carrying out real-life productivity investigations in a number of industrial environments where the lighting has recently been renovated. Realising 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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