Light & Engineering
Vol. 28, No. 1, pp. 4–22, 2020
https://doi.org/10.33383/2019-108
Svetotekhnika #2, 2020

TOPICS IMPORTANT FOR THE UP-TO-DATE INTERIOR LIGHTING PROFESSIONAL

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ABSTRACT

To avoid disappointments with LED lighting installations, detailed knowledge of the typical characteristics of the many different solid-state light sources is essential, while already long-available information on vision and colour seeing has to be combined with entirely new fundamental research on the relationship between lighting on the one hand and vision, performance, comfort, health and well-being on the other hand. Lighting has apart from visual effects also far-reaching non-visual biological effects. These effects influence the way our body "operates" and therefore, influence our health, well-being and alertness. Interior lighting installations today have to be designed so that they provide both suitable visual and non-visual biological effects, while adverse effects of lighting, like flicker, blue light hazard and disruption of the biological clock, are avoided.

LEDs offer the possibility to use them not only for lighting but also for data transmission. The use of LED lighting as a means for data communication is referred to as "light beyond illumination". Visible Light Communication (VLC), LiFi, and light itself used as sensor are part of this subject. The modern lighting professional has to get familiarised with these new technologies and applications.

The author of this article published in 2019 the book "Interior Lighting, fundamentals, technology and application" with Springer [1]. It discusses in 500 pages all topics important for the up-to-date interior lighting professional. The present overview article is entirely based on this book and follows the same chapter structure. Each chapter also describes, as an example, one or two crucial aspects in more detail.

Keywords: interior lighting, human-centric lighting, lighting and health, lighting and age, visual performance, visual satisfaction, therapeutic effects of lighting, hazardous effects of lighting, LEDs, interior lighting design

1. FUNDAMENTALS

1.1. Visual Mechanism

A visual sensation is the result of processes in the eye and brain. Light entering the eye is projected on the back of the inner part of the eye, the retina. The retina contains photoreceptor cells: cones and rods. Photopigments in these receptor cells absorb light, resulting in a chemical-electrical signal, which travels down a nerve into the visual cortex part of the brain where the visual sensation is invoked. A small area of the retina around the axis of the eye, the fovea, only contains cone cells. The other, peripheral, areas have few cone and many rod cells. The cone cells in the fovea have a one-to-one nerve connection to the brain. Rod photoreceptor cells are located in the periphery of the retina. Many of them converge on a single ganglion cell. Consequently, foveal vision is sharp and peripheral vision is not sharp.

The set of rods converging on the same ganglion, called the receptive field of that cell (Fig. 1), are processed through an opponent mechanism. Ganglion cells compare signals arriving from an inner circular area of the receptive field with signals arriving from the outer circular area (the surrounds) of the same receptive field. The centre-surround opponent processing by the retinal ganglion cells enables detection of light-dark transitions and thus edge detection of bright objects.

Fig. 2 -left illustrates this by showing how a bright circular object (or light source) of uniform luminance interacts with a group of receptive fields of neighbouring ganglion cells. Only the cells indicated in red are excited. This means that only the edges of the uniform bright area forward information into the brain. From the uniform parts of the light source, no information is forwarded to the brain so that the brain is less engaged. A multitude of smaller bright objects of light sources (Fig. 2 -right, like, for example, matrix LED luminaires) excites more ganglion cells by the larger number of edges and consequently engages the brain more, which, in turn, may be the reason for a higher degree of discomfort glare of LED-matrix luminaires. This phenomenon is now used to develop an entirely new fundamental basis for discomfort glare prediction. Preliminary results show promising results [2, 3, 4, 5].

Colour vision is possible because there are three types of cones, one with sensitivity for reddish, one for greenish and one for bluish light. A colour opponent mechanism processes their signals. This procession does not take place in the ganglion cells of the retina but in ganglion cells located at a kind of substation in the central part of the brain. It is called

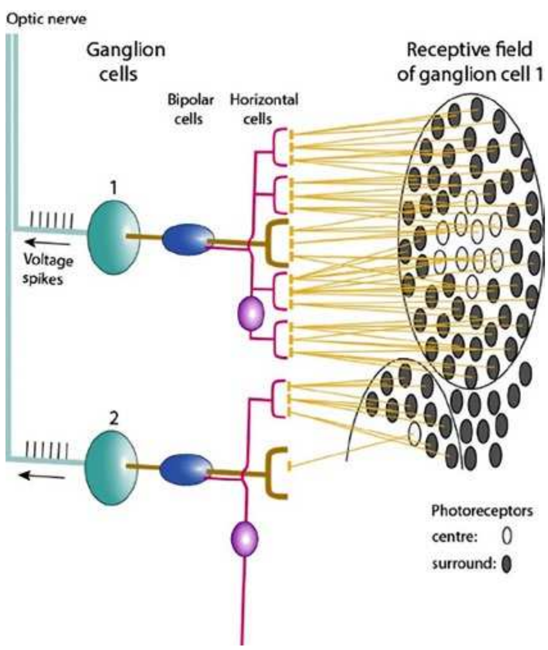

Fig. 1. Receptive fields of two ganglion cells

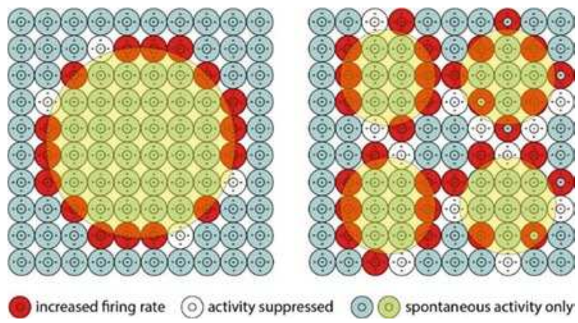

Fig. 2. Edge detection of a light source: the light source with a uniform luminance (left) excites fewer ganglion cells than the source with non-uniform luminance (right)

the lateral geniculate nucleus (LGN). This opponent colour mechanism with an opponent yellow-blue, green-red and white-black channel determines to a large extent how we perceive colours. Since we have just one type of rod cell, colour vision with rods is impossible.

Cones are mainly active at lighting levels larger than some 5 cd/m^2. Vision is then referred to as photopic. The spectral eye sensitivity curve *V(λ)* defined for photopic vision is the basis for all photometric units.

1.2. Colour

Solid-state light sources offer far more possibilities to engineer lamp spectra to suit different colour quality requirements than gas discharge lamps did. Accurate lamp colour specification based on perceived colour has therefore received renewed attention. This concerns in the first place the specification of different types of white light sources. Coloured LEDs are more and more used in interior spaces so that also an accurate specification of coloured light sources is needed.

The number "three" plays an essential role in colour vision. Examples are the three types of cones and the three-channel opponent colour vision system described in the previous section. Principally, all colours that can be produced by three primary colours can only be presented in a three-dimensional space. A simplification towards a two-dimensional plane presentation is possible by neglecting the effect of differences in brightness of the colour stimulus and concentrating on hue and saturation of the colour sensation only. With the two coordinates x and y, used in a rectangular coordinating system, the CIE1931 *x-y* chromaticity diagram (the well-known "CIE colour triangle") is constructed.

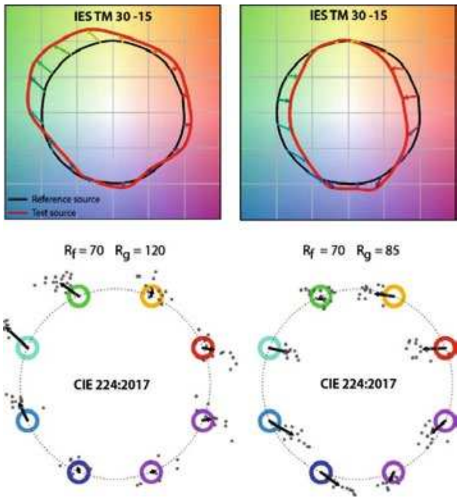

Fig. 3. IES TM 30–15 (top) and CIE224:2017 (bottom) [11] colour vector graphics visualising colour shifts as obtained with the same two light sources relative to their reference sources

Correlated colour temperatures of light sources, as a characterisation of the tint of whiteness, are easily obtained from the *x–y* chromaticity coordinates. MacAdam ellipses, in a more uniform *u′–v′* chromaticity diagram, are the basis for the binning process in the LED manufacturing process. More uniform means that an equal distance in the *u′–v′* diagram represents better a same perceived colour difference.

A wealth of new research on colour science is available as a basis to replace some colour concepts that have been developed between the 1930s and 1960s. New uniform three-dimensional colour spaces have been introduced. The CIECAM02-UCS colour space is proposed in report TM-30 of the IES of North America [6] as a basis for a novel two-metric colour-rendering system with a fidelity index R_f and a gamut index R_g. Many studies have shown that there exists a relatively good correlation between R_f and the CIE colour rendering index R_a, [7, 8, 9, 10]. However, with the possibility of engineering LEDs that emit light with small spectrum lines at specific wavelengths (for example with the use of quantum dots), the colour fidelity index R_f method is more "future-proof" than the old R_a method. The second metric, gamut index R_g of the two-metric system, is a measure of colour saturation. In some applications, a light source that shifts a particular colour or colours in a specific direction, for example towards more saturation and thus to more colourful colours, may make the visual scene more pleasant. If the gamut index is larger than 100, the colour shift is generally towards more saturation and if smaller than 100 towards less saturation. Colour vector graphics visualise the colour properties of light sources. They represent an indispensable new tool for the lighting designer in the LED era. The top of Fig. 3 shows the vector graphic diagrams proposed by IES-TM-30 [6] for two different light sources with the same fidelity index but with different gamut index. The colour shift is indicated by an arrow (the vector) relative to the black circle, which represents the reference source (no colour shift). The ends of the vectors are interconnected by the red line so that both the size and direction of colour shift in each part of the diagram are visualised. Where the line lies outside the circle of the reference source, saturation increases, and where the line is inside the circle, saturation decreases. So, the light source represented on the left of Fig. 4 (top) saturates green-yellow colours strongly and red-orange colours a little. On average, this light source results in strong saturation which is also clear from its high gamut index (R_g = 120). The light source on the right (top) results in strong desaturation of a large part of the colours (R_g = 85). In CIE publication [11] developed an alternative graph for visualising colour shifts (Fig. 3 bottom) that contains

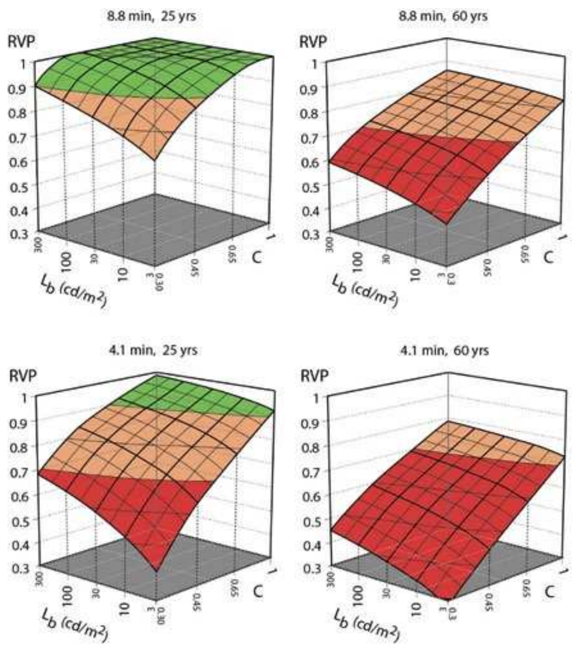

Fig. 4. RVP bodies: Relative Visual Performance (RVP) as a function of object contrast (C) and background luminance (L_b); top: visual angle 8.8 min (same size as an 8.5-point Times letter viewed from 50 cm); bottom: 4.1 min (same size as a 4-point Times letter viewed from 50 cm); left is the 25 years of age and right is the 60 years of age

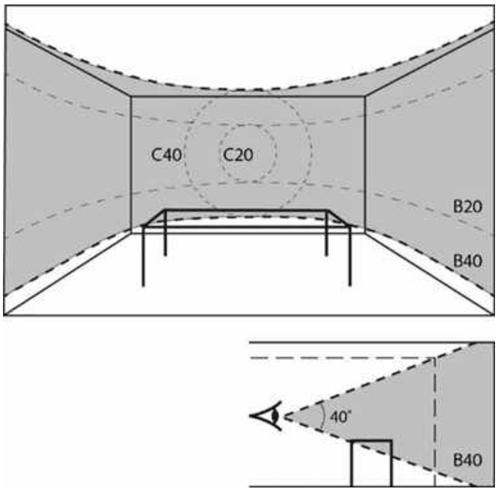

Fig. 5. Mock-up conference room with different dominant areas that were investigated in [20]

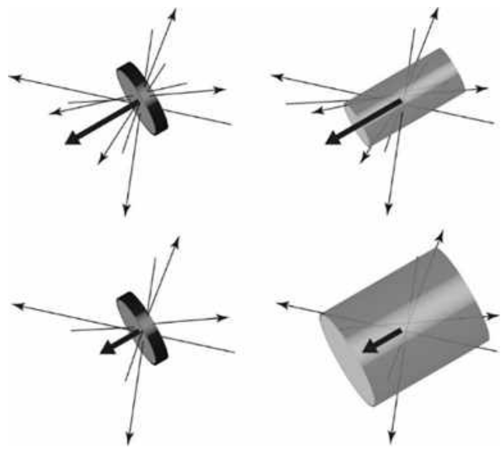

Fig. 6. Difference between light rays and light flow: small arrows represent light rays and the broad arrow the illumination vector; the diameter of the light tubes is inversely proportional to the magnitude of the vector: top: large illumination vector and corresponding small light tube; bottom: smaller illumination vector and corresponding wider light tube
Note: disks on the left are in reality infinitesimally small

more information about the spread of the results, which can be important for research reasons. The IES-TM-30 graphic is more intuitive and therefore more suitable for general use.

1.3. Visual Performance

Visual performance for tasks of different size and contrast as a function of background luminance provides information about what lighting levels in interior working situations are required as a minimum for efficient performance. In almost every human activity, visual performance should be well above its visibility threshold to perform efficiently. Efficiency depends on speed and accuracy with which visual tasks can be detected and identified. Many researchers have carried out suprathreshold investigations into the relationship between lighting level and speed and accuracy of work. The tasks used in these experiments vary from Landolt rings [12, 13] search tasks using test sheets with a random distribution of all numbers from 1 to 100 [14], verification tasks in which two printed number lists were compared [15, 16] and computer input data tasks [17]. CIE compared the different methods and concluded that the model based on Weston's data (Landolt ring tasks) provides the best prediction for visual performance under office conditions [18]. We, therefore, used Weston's studies as a basis to calculate relative visual performance (RVP) for different contrasts between task and background, and for different background luminances. Fig. 4 shows, for a visual angle of 8.8 min (same size as an 8.5-point letter seen from 50 cm) and 4.1 min (same size as a 4-point letter size from 50 cm), the so called RVP (Relative Visual Performance) bodies as calculated for observers of 25 and 60 years. For easy to moderately difficult tasks, as occurring in many offices, it is shown that visual performance is not a key issue for determining what lighting level is required for young persons. In situations with more difficult visual tasks, visual performance becomes an issue. Visual performance of older workers deteriorates considerably, and their performance should always become a consideration in setting lighting levels.

Disability glare, which is the form of glare that is responsible for a negative influence on visual performance, has a neglectable effect on visual performance under most interior lighting conditions. Glare in interiors should be limited by restricting discomfort glare. Discomfort glare will be discussed in the next Section 1.4: "Visual Satisfaction".

The spectrum of light influences the threshold performance measure of visual acuity through its effect on the size of the pupil. Under many working conditions, however, this is of limited relevance since most of the visual tasks are far above the threshold of visibility where the spectrum hardly plays a role [19].

1.4. Visual Satisfaction

Visual performance, as described in the previous section, relates to the lighting of the task. The

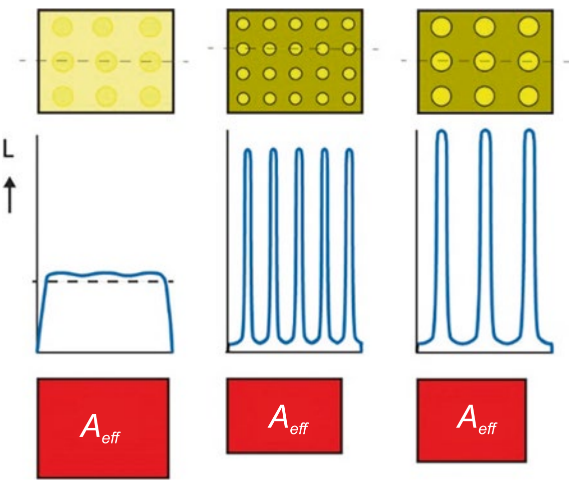

Fig. 7. Illustration of the effective light-emitting area of a luminaire, A_{eff}, as defined by CIE (2019) [32] for non-uniform luminaires to be used in the standard UGR discomfort glare formula

lighting of the whole space determines whether the overall appearance of the space is experienced as visually satisfying. The brightness of a space, the distribution of the luminance in that space, the directionality of the light, the degree of discomfort glare and the colour tint of light determine visual satisfaction.

For the characterisation of the visual appearance of a room two different metrics are proposed: the average luminance in a horizontal band with a width of 40° [20, 21, 22, 23] and the mean room surface exitance [24, 25, 26]. Fig. 5 shows the mock-up room used by Loe et al. [20] to study how well different "dominant" areas define the visual satisfaction of a room. B40 showed the best correlation.

The directionality of lighting determines the appearance of three-dimensional objects and faces in a space. The concept of flow of lighting, illustrated in Fig. 6, allows for the calculation of the lighting's main direction and strength at a point in space as a result of all light rays at that point. The vector-to-scalar ratio can quantify, and light tubes visualise, the flow of lighting. The latter enables a detailed analysis of the spatial and form-giving potential of lighting designs. With today's available computer graphic software, methods for light tube visualisations of complete lighting installations have been developed [27, 28, 29, 30, 31]. Such software may become an indispensable tool for the modern lighting designer to check the lighting effect at literally every point in the space.

The unified glare rating UGR concept is used as a measure of the degree of discomfort glare. However, the UGR concept needs modifications for glare sources with a non-uniform luminance, such as many LED matrix luminaires. As mentioned in Section 1.1 (Fig. 1), some researchers have recently used as a basis for their discomfort glare considerations the neural response to bright light and the mechanism of receptive fields. The process of neural signals being transformed in ganglion cells into edge detection signals (Fig. 2) is a promising candidate for quantifying discomfort glare from a fundamental physiological point of view. A CIE Technical Committee very recently defined a temporary correction of the UGR method until a fundamental approach based on physiological and psychological mechanisms provides practical results. The Committee concluded that the preferred correction method for UGR is the use of "effective light-emitting area" in the standard (unchanged) UGR formula [32]. The effective light-emitting area, A_{eff}, is determined from a high-resolution luminance image of the luminaire. For non-uniform luminaires, the effective light-emitting area is smaller than the physical light-emitting area, as illustrated in Fig. 7. The measurement and calculation procedure is described in detail in the corresponding CIE publication [32].

The spectrum of the glare source influences also discomfort glare: short-wavelength light sources result in more discomfort glare than long wavelengths.

The correlated colour temperature-based rule of Kruithof [33] works not good enough to predict visual satisfaction with light sources of different tints of whiteness.

1.5. Non-Visual Biological Mechanism

Daily (circadian) bodily rhythms, a fundamental property of human life, are synchronised by the natural 24-h dark-light rhythm. This entrainment by light is one of the non-visual biological effects of light. Without entrainment, the bodily rhythms will deviate from the 24-h rhythm. This misalignment will have negative health consequences, in particular on sleep quality. It also will result in lower alertness and performance during daytime.

An, until recently, unknown type of photoreceptor discovered in 2002, the photosensitive retinal ganglion cell pRGC, connects with the suprachiasmatic nucleus SCN, a structure within the brain that acts as a master biological clock [34]. The SCN, in its turn, has pathways to the pineal gland, where melatonin is produced, and to the adrenal cortex responsible for the production of cortisol. The hormones melatonin and cortisol govern sleep and alertness. Cortisol increases glucose to give the body energy. It is sometimes, popularly, referred to as the energy hormone. Melatonin slows down some bodily processes and evokes sleep. Melatonin, popularly called the sleep hormone, reaches, in the case of proper entrainment, its maximum level in the middle of the night and is, again in the case of proper alignment, nearly entirely absent during daytime. Cortisol, which produces glucose, provides the body with energy. It should have a sufficiently high level during daytime and reach its minimum during nighttime.

Light may, apart from effects on circadian rhythms, also have direct, acute photobiological effects that directly influence alertness and performance.

The spectral sensitivity of the pRGCs, given by their photopigment melanopsin, is different from that of rods and cones. Its sensitivity peaks in the blue part of the wavelength range. Rods and cones have a neural connection with ganglion cells, and consequently, their signals interplay with the signal obtained from the pRGC itself (Fig. 8). Much of this neural wiring is as yet unknown. Primarily because of this, it is impossible to define a single spectral sensitivity function or action spectrum for all non-visual effects of light. The correlated colour temperature can be used only as a rough indication for the characterisation of the spectrum of lamps for non-visual biological use. The spectrally weighted irradiances for the five human photopigments together are the best characterisation. Of these five, the pigment of the ipRGC, called melanopsin, is the more important one as far as non-visual biological effects are concerned.

The absorption spectra of the cones and rods are already long time known. CIE defined the spectral "melanopic sensitivity" based on measurements of the absorption spectrum of the photopigment melanopsin in its international standard CIE026:2018 [35].

The collective name for the five spectral weighted irradiances is "α-opic irradiance". Each of the five individual α-opic irradiances is named after its photopigment name, melanopic (pRGC), rhodopic (rod), cyanopic (S-cone), chloropic (M-cone) and erythropic (L-cone) irradiances. Fig. 9 gives for some lamp types the calculated α-opic irradiances for the five photoreceptors, for the condition

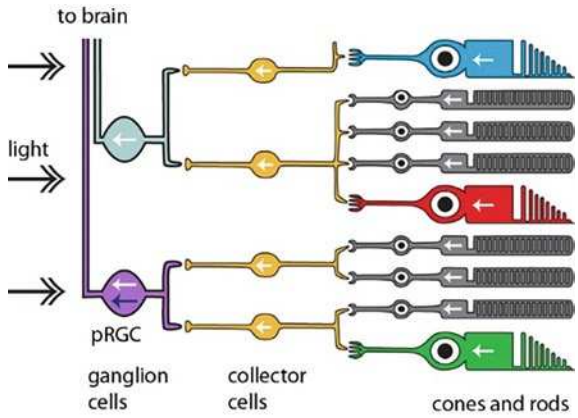

Fig. 8. Part of the retina with photoreceptor cells, including photosensitive retinal ganglion cell, pRGC (in purple). White arrows represent signals to the brain as a result of the transformation of light incident on cones and rods, the blue arrow represents the signal from light incident on the opsin melanopsin of the pRGC

1000 lx at the outer surface of the eye. These five "irradiances per 1000 lx" give a good insight into the effectiveness of a lamp in evoking a reaction in each of the five photoreceptors. For non-visual biological lighting applications, it may often be interesting to compare the melanopic irradiance of a particular light source with the melanopic irradiance by daylight (of the same lighting level at the eye). For this purpose, Fig. 9 also gives, for each lamp type, the "melanopic equivalent daylight ratio Melanopic equivalent daylight (*D65*) factor DL_{eq}". It is the ratio of the melanopic irradiance of the lamp to the melanopic irradiance of 6500 K daylight (CIE standard *D65* sky). This ratio is also referred to as melanopic daylight (*D65*) efficacy ratio (CIE2018) [35].

1.6. Light, Sleep, Alertness and Performance

A classical sleep model is based on an interaction of two different processes. A homeostasis process is characterised by increasing and decreasing sleep pressure after waking up and while asleep, respectively. The other process is a circadian one which provides the possibility to sleep: the sleep window. Light and darkness at the appropriate times strongly influence the latter process: daytime light influences sleep possibility during the subsequent night. Here, both the level and the spectrum of light play a role. Cooler white light is more effective than warmer white light.

Light affects sleepiness, alertness and performance during daytime through two different routes (Fig. 10). Route 1 represents the circadian route de-

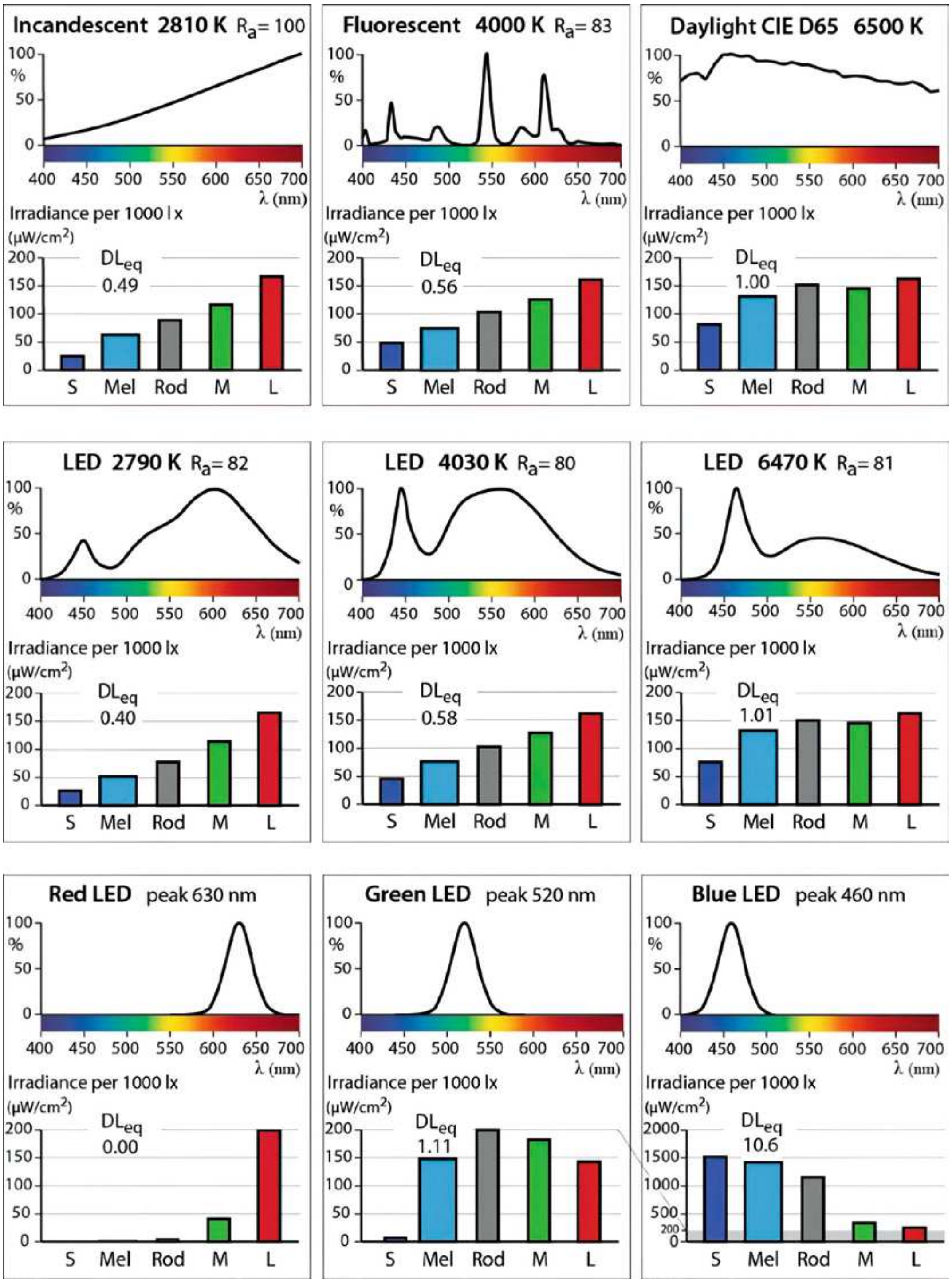

Fig. 9. Alpha-opic irradiances of different lamp types for 1000 lx at the outer surface of the eye: S (S-cone) is cyanopic irradiance, Mel (melanopsin) is melanopic irradiance, Rod is rhodopic irradiance, M (M-cone) is chloropic irradiance and L (L-cone) is erythropic irradiance, DLeq is the melanopic equivalent daylight ratio (CIE D65); bars for melanopic irradiances are shown somewhat broader to make them stand out

scribed above and route 2 the direct photobiological one. Route 1 starts at the moment of daytime light on the previous day ("yesterday"). Daytime light of yesterday affects the night-time sleep quality of yesterday, as discussed in the previous chapter. Therefore, the daytime lighting of yesterday influences sleepiness, alertness and performance of today. Route 2, the direct photobiological route, concerns light that invokes an acute activating effect as long as the lighting is available because of direct photobiological processes. A dynamic lighting scenario for daytime workplaces, which dynamically

Table 1. Three Causes for Circadian Misalignment in Shift Workers

Nighttime lighting:	horizontal illuminance of 500 lx not effective in phase shifting
Daytime lighting before and after daytime sleep:	Bright daylight helps to stay entrained to the natural day-night rhythm
Days off:	Switch back from "nighttime work" and "daytime sleep" to the natural day-night rhythm

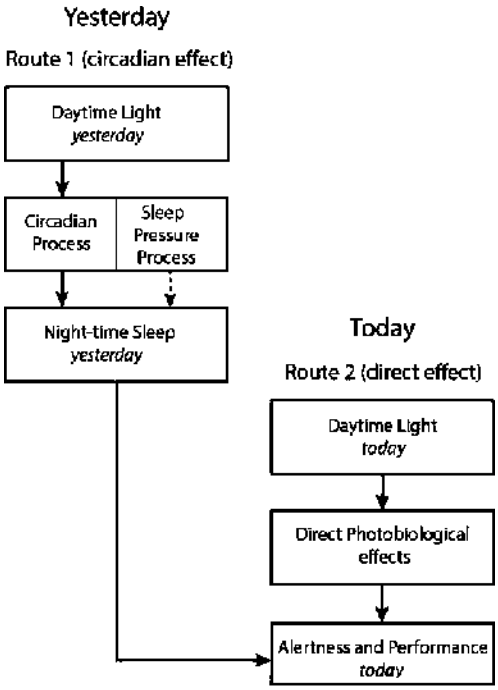

Fig. 10. Two routes through which daytime light may influence daytime alertness and performance

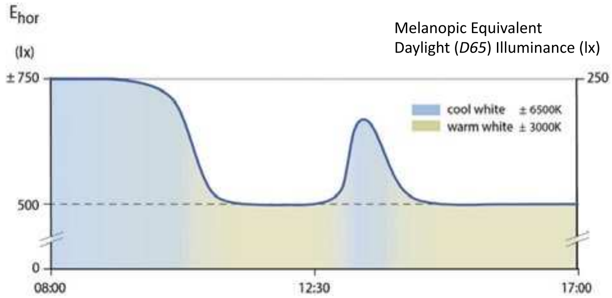

Fig. 11. Lighting scenario for human-centric lighting in offices: the value of 250 lx melanopic equivalent daylight (*D65*) illuminance is the basis for the scenario. It corresponds to roughly 750 lx horizontal illuminance (for 6500 K, conventional type of light distributions and luminaires arrangement); the value of 500 lx for 3000 K corresponds to roughly 85 lx melanopic equivalent (*D65*) illuminance

changes both the lighting level and colour to ensure the positive effects of the two routes, is proposed in Fig. 11. It optimises between energy requirements on the one hand and requirements of visual and non-visual effects of lighting on the other hand.

1.7. Shift Work, Light, Sleep and Performance

The circadian rhythm of most night-time workers who work under no extra bright light does not shift much [36, 37, 38, 39, 40]. It leads to a mismatch of the body circadian rhythm and the night-time work–daytime sleep rhythm. The body is as far as its circadian phase is concerned in the "biological night" at the moment it has to work and in the "biological day" when it has to sleep. Table 1 lists the most important causes for the misalignment. The phase shift and thus, misalignment between the body circadian rhythm and the work-sleep rhythm have adverse effects on the health of the shift worker. It also affects sleep, alertness and performance adversely. Specifically designed shift work lighting can help reduce these problems. The night shift is considered to be the most disruptive one.

Depending on the duration, timing and rotating frequency of shifts and of the risk of work, the objective of shift work lighting is different. For permanent night-shift work and slow-rotating shifts, the goal should be a complete resetting of the circadian rhythm. For fast-rotating shifts, with change over periods of some 3–7 days, usually partial or compromise phase shifting offers an adequate possibility that also allows the shift worker to have a relatively normal social life. The circadian rhythm of workers in single-night shifts or very-rapid-rotating shifts should preferably not be phase shifted. These objectives can only be obtained with different lighting schedules. Recent research results are available as a basis for such schedules. Some lighting schedules use bright white light of gradually changing colour temperature; others use intermittent very bright light pulses of relatively short duration and again others, light of which the short wavelengths are filtered (short-wavelength depleted white light).

1.8. Age Effects

The changes that occur with age in the optics and retina of the eye, and in the neurological pathways into the brain, have thoroughly been investigated

Table 2. Combined Effect of Reduced Pupil Size and Reduced Eye Transmission due to Lens Yellowing on Light Reaching the Retina of Older Persons Relative to a 25-Year-Old, for Phosphor LEDs with CCT of 2700 K and 6500 K at an Adaptation Level of 10 cd/m² and 100 cd/m²

Age	Transmission for 2700 K		Transmission for 6500 K	
	L_{adapt} = 10 cd/m²	L_{adapt} = 100 cd/m²	L_{adapt} = 10 cd/m²	L_{adapt} = 100 cd/m²
50 relative to 25 years	0.84	0.91	0.83	0.90
65 relative to 25 years	0.75	0.86	0.72	0.83
80 relative to 25 years	0.65	0.78	0.63	0.76

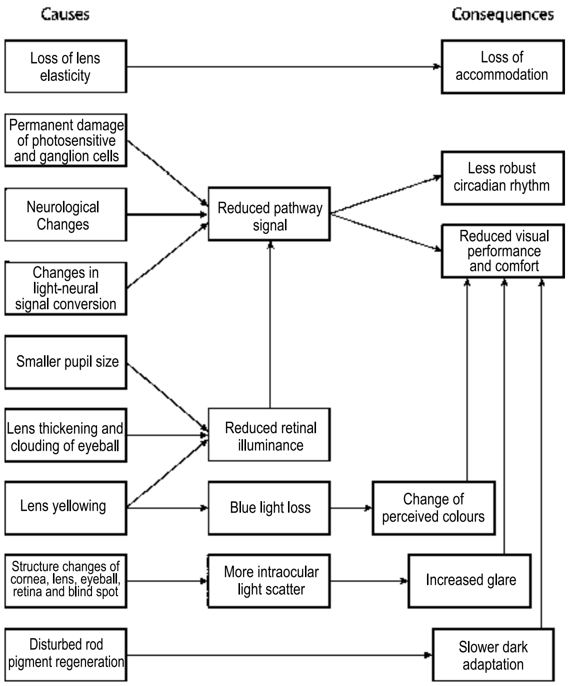

Fig. 12. Causes and consequences of the adverse effects of the ageing eye

and are well documented [41, 42, 43]. These changes have adverse effects on vision and on the circadian system. Fig. 12 lists the causes of these adverse effects together with the adverse consequences for the visual and circadian system.

The optical changes in the eye with age concern loss of eye-lens transparency because of yellowing of the lens, structural changes in the cornea and eyeball (clouding), and a smaller pupil size due to loss of elasticity. They all have negative consequences for the amount of light reaching the retina. The effect of the yellowing of the eye lens also leads to loss of blue light which is especially a problem for both acute and circadian non-visual effects of light. Structural changes of the cornea, lens, vitreous body, retina and blind spot increase the scattering of light by these structures towards the fovea and consequently increase glare in the elderly. With increasing age, regeneration of the rod pigment takes more time, and consequently, dark adaptation is slower.

Table 2 gives the combined effect of reduced pupil size and reduced transmittance of the eye due to lens yellowing for an adaptation luminance of 10 and 100 cd/m², for a phosphor LED with a CCT of 2700 K and 6500 K, respectively (R_a > 80).

1.9. Therapeutic Effects

Light can sometimes be a therapy for a disrupted circadian system. Light therapy, specifically timed exposure to light, is a particular form of chronotherapy. Sometimes, light therapy does not cure the disease itself but helps to reduce negative symptoms of the disease.

SAD is the first disease that was treated successfully with light therapy, nearly 35 years ago [44]. Seasonal affective disorder (SAD) is a type of mood disorder in which people with normal mental health experience severe depressive symptoms during the same period each autumn or winter. SAD is sometimes referred to as winter depression. SAD related problems usually disappear after two weeks of daily clinical light therapy of white light of 2500 lx for some two to three hours or 10.000 lx for 30 to 45 minutes [45].

In some cases, specific interior lighting can be applied as light therapy, next to its task of providing proper visual conditions. Light therapy for depressions (seasonal and non-seasonal), sleep disorders, sleep disorders connected with Alzheimer's and Parkinson's disease, attention-deficit hyperactivity disorders (ADHD) and eating disorders are examples of this. In demented patients, the usual circadian sleep-wake rhythm becomes often disturbed, in particular in patients with Alzheimer's disease. Nighttime sleep is fragmented, and daytime activity is intermixed with napping. Nighttime wandering and daytime aggression rather often accompany these symptoms. All these side effects of Alzheimer's disease can often be relatively well treated with light therapy by specific interior lighting in the room of the patient [46, 47, 48]. As an illustration of the positive effects that can be obtained with light therapy for Alzheimer patients, Fig. 13 shows the activity data, measured with an action watch, of an Alzheimer patient who participated in a classical study on this subject [49]. For the actual patient, the measured number of movements per hour is displayed on the vertical axis, while the horizontal axis gives the time for five consecutive days. The upper graph, measured before the treatment of the patient, shows the typical irregular sleep-wake rhythm of an Alzheimer patient. The lower graph gives the situation near the end of the light treatment period of the same patient with white light during each day (morning and afternoon) of an average illuminance at the eye of 1140 lx (4100 K). The variability of the activity pattern is considerably reduced with much activity during daytime and little activity during nighttime.

Irregular light-dark rhythms quite often occur in the patient rooms of hospitals. Specifically designed daytime artificial lighting that supplements daylight entering the patient room can improve the sleep quality and mood of the patient and reduce the length of stay in the hospital.

1.10. Hazardous Effects

1.10.1. Lamp Flicker

Visual adverse effects because of lamp flicker fall into three categories: visible flicker effects, stroboscopic effects and phantom array effects.

Visible flicker stands for the annoying visual impression of unsteadiness induced by light whose luminance fluctuates with time. The term "visible flicker" is usually shortened to just "flicker". The stroboscopic effect relates to the change in the perception of moving objects under flickering light. When a static observer looks to a continuously moving object, the object is typically seen as moving continuously and smoothly. However, under certain forms of flickering light, such an object is perceived as moving discretely, i.e. jump-wise in staccato. Where the stroboscopic effect is caused by moving objects, the phantom array effect may arise with non-moving time-modulated lights when the eyes move across these lights. In addition to the real lights, non-existing phantom or ghost lights may appear. A typical situation where the phantom array effect may arise is when driving behind a car of which the two rear lamps have a bad light-modulated waveform. The lamps are seen as an array of many more than two bright red lights stretched out around the car.

A metric to characterise the severity of visible flicker is the "short-time flicker severity", P_{st}. [50], produced a standard that gives a functional and design specification for a flicker-measuring apparatus: the IEC flickermeter that measures P_{st}.

A metric for the stroboscopic effect is described as the "stroboscopic visibility measure", SVM [51, 52].

The phantom array effect can only occur in situations of high contrast between the light source and its background, with light sources smaller than two degrees while viewing directly into it. These situations are typical for night-time outdoor situations and do not occur in interior lighting applications.

Modern luminance and spectrophotometers can measure in an installation the frequency of flicker. Some can visualise the time-modulated light graph. Accurate meters for the measurement of the metrics P_{st} and SVM have been developed. A kid's spinning top can easily be made into a simple tool to check whether the light of a particular lamp contains flickering frequencies. For this purpose, the surface of the top must be provided with small white rectangles regularly distributed in one or more rings on a black surface (Fig. 14).

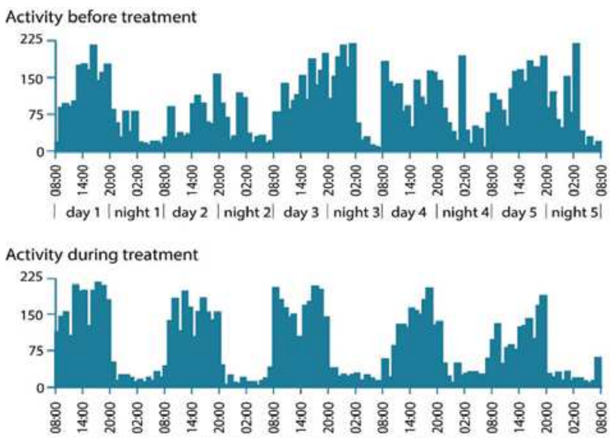

Fig. 13. Activity per hour shown for a period of two times 24 h of an Alzheimer's patient with at the top the data before treatment and at the bottom after 2 weeks of treatment with light during the whole day of an average illuminance of 1140 lx on the eye [49]

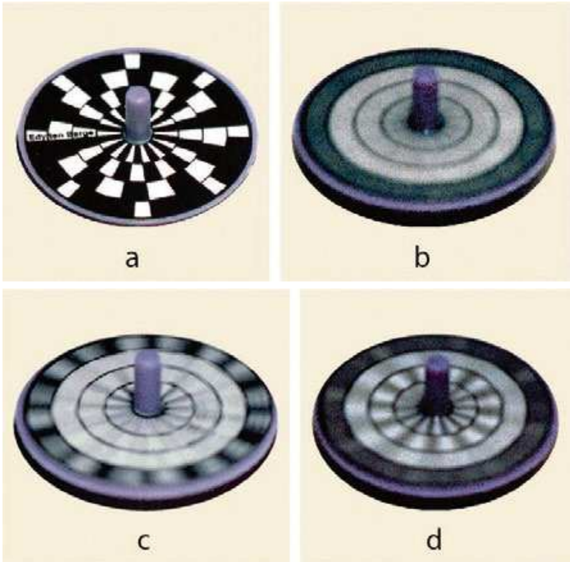

Fig. 14. Spinning top used to check whether or not light contains flicker frequencies; blurred rings at all spinning speeds (b): no flicker frequencies; static white-grey rectangles at some spinning speeds (c, d): the light contains flicker frequencies (design of the top's surface: Edy ten Berge)

1.10.2. Blue Light Hazard

The wavelengths range of (400–500) nm of light associates with a relatively strong photochemical effect in retinal tissues. This range corresponds to blue light. The possible hazard associated with this visible wavelength range is therefore called "blue light hazard". CIE (2002) [53] has defined a system of blue light hazard risk groups for light sources. It is based on the action spectrum (sensitivity spectrum) for retinal damage risk by visible light of different wavelengths. A survey of recent publications on the subject shows that the blue light hazard is not an issue in general lighting that uses white-light sources, including white LEDs [54, 55, 56, 57].

1.10.3. Bright Light at Night

Bright light at night has the potential to disrupt the circadian rhythm which in turn could have adverse effects on health in the form of gastrointestinal, cardiovascular, metabolic (diabetes and obesity) disorders and possibly cancer. In this context, bright light is lighting level of at least 300 lx horizontal illuminance. Van Bommel's Interior Lighting book [1] summarises research in animals and epidemiological studies with humans to provide information about a possible link between cancer and bright light at night.

2. TECHNOLOGY

2.1. Lamps, Gear and Drivers

Today, for almost all lighting applications, LEDs have taken over from all traditional light sources including gas-discharge lamps. This is in particular for reasons of efficiency and long lifetime.

Quality LED light sources have nowadays such a long life, 50,000 hours and longer, that it is not the failure rate that determines how long the LED light source continues to provide lighting up to specification. It is, in particular, the LED parameter "lumen output" that determines operational life. When the lumen output becomes so low that the LED light source has to be replaced, that LED source has a so called parametric failure, although the LED source may continue to function for a much longer time. IEC defines LED lifetime by the parametric failure: "too low lumen output" (IEC2015) [58]. The moment at which the LED light source completely stops functioning is referred to as an abrupt or catastrophic failure. LED lifetime (by "too low lumen output") is specified as *Y* hours of useful life based on the condition *Lx* B_{50}. Here *Y* is the time (in hours) after which 50 % (B_{50}) of a population of LED modules parametrically fails to provide at least a percentage *x* of the initial luminous flux. If only the *Lx* value is given (what is usually the case), *B* is assumed to be 50, meaning that 50 % of a set of LEDs of the same type failed to deliver the declared percentage *x* of lamp lumen, i.e. B_{50}. Which lumen depreciation percentage is relevant, is dependent upon the type of application. L_{90}, L_{80} and L_{70} are values that may be relevant, and lifetime specifications without such *Lx* indication are senseless.

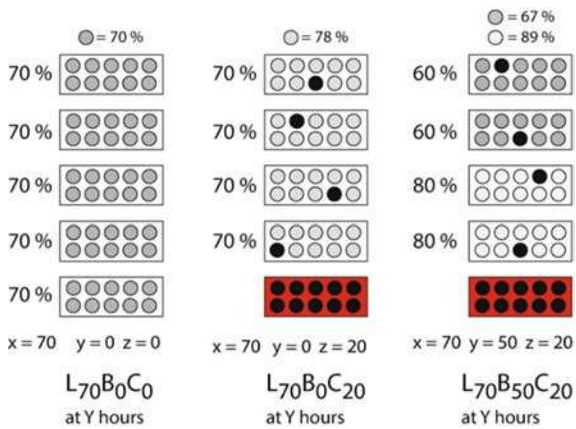

Fig. 15. Examples of different *LxByCz* conditions of a LED module

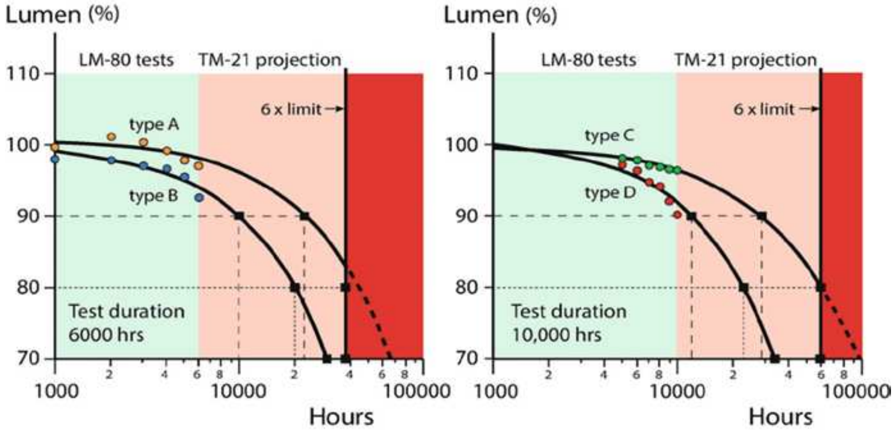

Fig. 16. Examples of lumen maintenance interpolated curves for four different LED types according to IES TM-21, calculated from measurement points obtained from tests based on IES LM-80; the coloured circles are measuring points; the black squares represent the projected lifetime for the conditions L_{90}, L_{80} and L_{70}

An essential point in the IEC standard is that it considers failures of single LEDs in a multi-LED module to contribute to the gradual lumen output degradation. The effect is incorporated in the lamp lumen depreciation and thus in the *Lx* condition. Abrupt, catastrophic, complete failures of a LED module are referred to as *Cz*: length of time during which *z*% of a population of LED modules of the same type fail to produce any luminous flux. Fig. 15 gives typical examples of different *LxByCz* conditions for a LED module.

The industry standard for lumen maintenance testing of a batch of LEDs is IES Document LM-80 [59, 60]. The IES LM-80 documents prescribe the LED sampling method, the laboratory environment conditions, the photometric measurement protocol and the operating conditions (electrical and thermal) of the LEDs to be tested. The tests of one batch shall be done for at least 6,000 hours with data collection at a minimum of every 1000 hours. However, 10,000 hours (or more) are preferred for improved predictive modelling. A LED type has to be tested at a minimum of two LED case temperatures which have to be specified by the manufacturer based on the recommended operating condition. However, one of the two case temperatures shall be 55 ºC or 85 ºC to allow for mutual comparison of results, also between different manufacturers.

Tests according to document LM-80 provide no lifetime of the LED type tested. The data obtained are the input for another IES document, TM-21 [61], that predicts through interpolation of the LM-80 data, useful life. The latter report permits for a prediction of the lumen maintenance percentage at a life six times that of the tested period (based on a minimum sample size of 20 pieces). More extended predictions are unrealistic because of limitations in the extrapolation and lack of confidence in the data beyond. For an LM-80 tested period of 6000 h, this corresponds to a prediction for maximum 36,000 h. For a tested period of 10,000 h, the prediction is for maximum 60,000 h. The measuring points of the last 5000 h of the LM-80 test are used for the prediction. (For a test period of more than 10,000 h, the data of the last 50 % of the total duration are used). Shorter measurement intervals than 1000 hours provide, of course, more accurate results and are therefore preferred. Fig. 16 shows an example of the result of the mathematical interpolation for a test sample of 20 LEDs of four different

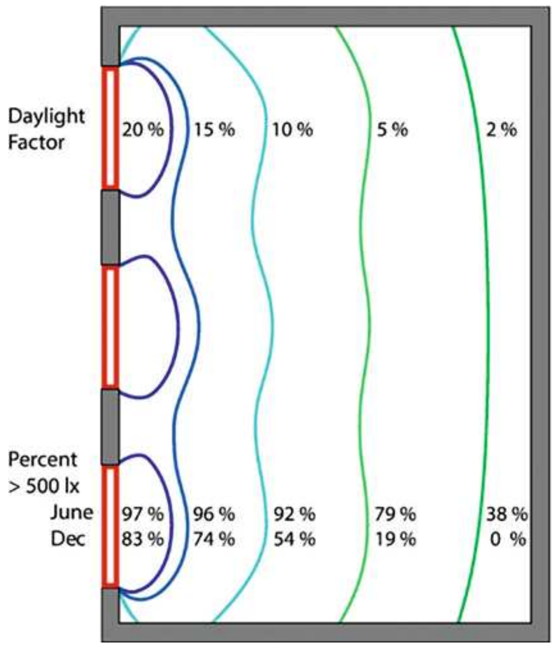

Fig. 17. Daylight factor contours for an office of 5.4×3.6 m with window height and vertical position (as for the window shown in red in Fig. 12.7 in [1]); at the bottom, the corresponding percentages of the time that more than 500 lx will be obtained, are given for June and December (based on daylight measurements in Bratislava, Fig. 12.3 right in [1])

Table 3. Lifetime Values for the Conditions L_{90}, L_{80} and L_{70} of the Four LED Types of Fig. 16

LED type	Test duration, h	life for L_{90}, h	life for L_{80}, h	life for L_{70}, h
A	6000	22,000	> 36,000	> 36,000
B	6000	10,000	20,000	30,000
C	10,000	28,000	60,000	> 60,000
D	10,000	12,000	22,000	33,000

LED types. Two of them are tested over a period of 6000 hours (Fig. 16-left) and two over 10,000 hours (Fig. 16-right). Table 3 gives for each type the projected values of L_{90}, L_{80} and L_{70}.

2.2. Daylight

Light is emitted at the outer layer of the sun, the photosphere. Due to the earth's atmosphere, we also receive indirect sunlight that is scattered from microscopic particles in the earth atmosphere, which makes the sky bright and bluish. The daylight varies with the sun's position, which is dependent on the time of the year and day and on the location on earth. Weather conditions influence the sky condition and therefore, also the daylight level and spectrum.

CIE has defined spectra for a series of standard illuminants that represent the spectra of daylight of different correlated colour temperatures [62, 63]. Daylight *D65* with a correlated colour temperature of 6500 K is the most known type. The correlated colour temperature varies not only with the sun's position but also with the presence and position of clouds and with the viewing direction of the observer. Table 4 gives an indication of the variation of the correlated colour temperature of daylight for different conditions.

CIE also defined different standard luminance distributions of skies for the purpose of daylight calculations [64]. The CIE standard overcast sky is usually used to determine the daylight factor that predicts the potential of daylight in buildings depending on exterior obstructions, fenestration and interior inter-reflection. At many locations on earth, daylight measurements have been made that give quantitative data on the amount of daylight. By combining these location-specific data with daylight factors, detailed insight is obtained in how much of the time and where in a lit space, sufficient daylight will be present. The daylight factor is defined as the ratio of the illuminance at a point in an interior space on a given plane due to the light received from a sky of a defined luminance distribution (excluding direct sunlight), to the illuminance on a horizontal plane in the open outside (without obstructions). The daylight factor is dependent on the dimensions and locations of the daylight openings in the building and of the position in the building. Usually, the CIE overcast sky and the horizontal plane are used as the standard situation. As an example, Fig. 17 gives daylight factor contours for a typical one- or two-person office room. The daylight factor at a specific point in the room gives the daylighting potential of a building at that point for the poorest type of sky represented by the CIE standard overcast sky. What the actual illuminance at that point will be depends on the time of the day, the time of the year and the actual location on earth (sun position). As an example, the daylight factors of the contours in Fig. 17 have been converted based on daylight availability data of Bratislava, into percentages of the time that more than 500 lx horizontal illuminance is obtained in June and December respectively.

2.3. Luminaires

The optical system of a luminaire may make use of mirrors (reflectors), micro lenses (refractors) and diffusers. With the introduction of LEDs, another possibility, that of total internal reflection (TIR), can also be used to produce precisely controlled beams. Total internal reflection may occur if light travels from a medium with a higher optical density to a medium with a lower optical density, i.e. from high to low refraction index. Glass and plastics have higher refraction index values than air. This means that at the boundary between the medium and air, refraction is away from the normal to the boundary layer, as shown in Fig. 18-left. The middle picture of Fig. 18 shows the situation where the light incidence angle is such that the refraction angle is 90° and thus parallel to the boundary surface. That in-

Table 4. Approximate Indication of Correlated Colour Temperatures (CCT) of Midsummer Daylight under Different Conditions

Shortly before sunrise	±4000 K
Shortly after sunset	±4000 K
Sunrise and sunset	±2000 K
Direct midsummer sunlight (midday)	5800 K
Overcast sky	(5500–6000) K
Shadow in clear sky (midday)	(7000–8000) K
Clear sky (midday)	(9000–30,000) K
Clear sky (midday)	(9000–30,000) K

cidence angle, corresponding to 90° refraction, is called the critical angle. It varies, depending on the type of plastic or glass, between approximately 30° and 40°. If light incidence is larger than this critical angle, light cannot leave the medium and is reflected with a very high reflection percentage (nearly 100 %) as shown in Fig. 18-right.

Total internal reflection with its extremely high reflectance is often used in combination with LEDs to produce efficient and precisely controlled beams in downlight and small floodlight type of luminaires. Often this TIR-optics is combined with a collimator lens. Fig. 19 shows an example of such a "hybrid" TIR-lens system. The TIR part controls the largest part of the light radiated from the LED chip, while the integrated collimator lens, located in the centre of the system, controls the light radiated from the chip into the central directions.

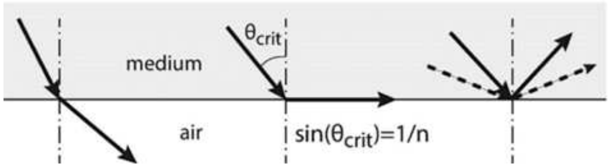

Fig. 18. Refraction and, for $\theta > \theta_{crit}$, total internal reflection (TIR)

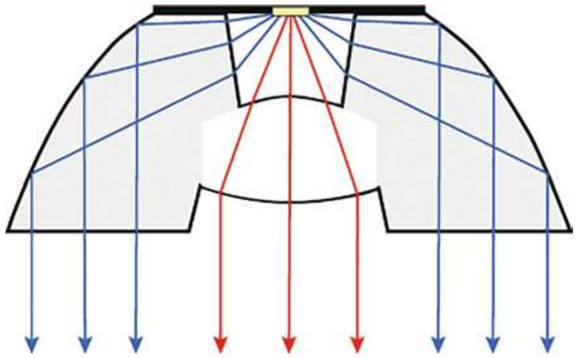

Fig. 19. Example of a rotation-symmetrical TIR lens solid body for an LED; blue rays are the result of TIR and red rays the result of the integrated collimator lens (indicated with a lighter tint)

2.4. Connected Smart Lighting

Connected smart lighting refers to lighting installations in which the luminaires, with integrated sensors, are interconnected in a wired or wireless network to both control and monitor the lighting. Microcontrollers and many sensors, like light, occupancy, temperature, humidity and noise sensors, are small enough to be incorporated in a luminaire. In this way, the luminaire becomes both a source of light and information. Connected, smart lighting systems using such luminaires can be used for many more purposes than energy conservation alone. By collecting, for example, data on the actual use of a space and the movement of people, automated space management is possible while ensuring user satisfaction. The sensors used in the smart lighting network can be expanded with sensors that measure parameters needed for other installations in the building such as temperature, humidity and air quality sensors. The smart lighting network so becomes the "heart" of a smart building.

Smart networks can use many different protocols for communication between all the connected devices. For wired networks, the 0–10 V DC, DALI, DMX 512 and DMX 512-RDM protocols, and for wireless networks, for example, the ZigBee, Bluetooth and Wi-Fi protocols. Fig. 20 shows an example of a ZigBee network.

Ethernet data communication cables can be used, simultaneously, for data communication and for supplying power to connected electric devices including LED luminaires: power over Ethernet (PoE). The latest standard of IEEE (2018) increases the maximum power to 90 W per connected device. This is possible because this standard allows for data over all four pairs of the ethernet wires. Since the power is DC and the data communication signals are of high frequency, there is no interference between the data and power signals over the same cables. Power of 90 W makes it possible to provide power for LED luminaires over ethernet in many smart lighting installations. The use of a separate mains power cable net is thus no longer needed. It reduces cable and installation costs considerably, makes the system more robust and simplifies maintenance and making changes.

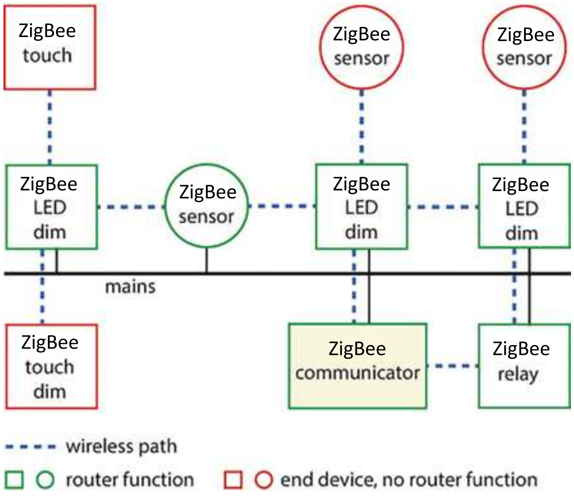

Fig. 20. ZigBee wireless network with a coordinator, devices with a router function to their neighbour devices embedded in smart lamps and sensors, and end devices without a router function

2.5. Light beyond Illumination

Light from LED luminaires can be used simultaneously for lighting a room and for wirelessly transferring data in that room. The term used for this emerging kind of wireless data transfer is "Visible Light Communication, VLC". For VLC purposes, the light is encoded and modulated without affecting the illumination quality. Of all light sources, only LEDs are suitable for visible light communication. This is because the luminous flux of LEDs varies nearly instantaneously with a variation of current through the LED. Only in this way, light can be modulated at high speed, i.e. the light "on" and light "off" condition can be produced at extremely high frequencies.

VLC can be extended into a bidirectional data communication system with a down- and uplink. It is referred to as Li-Fi. It is a much-needed alternative for, or a complement to, the congested Wi-Fi wireless communication system. Of course, it would be disturbing if for the uplink visible light is used. Disturbing light beams would be radiating from all connected devices in the room, such as PCs, laptops and smartphones. So, while with Li-Fi, the downlink indeed uses visible light, the uplink uses either invisible infrared radiation or Wi-Fi (Fig. 21).

The dual function of LEDs enables, apart from data communication, many new applications. Examples are the use of room lighting for indoor navigation and for sensing objects in a room. Using light as a sensor with only the light itself enables the determination of the contours of objects and even the pose and movements of persons (sitting, standing, laying, and walking). This information, in turn, can be used as input for all kinds of automated reactions.

3. APPLICATION

3.1. Lighting Quality and Standards

The quality of an interior lighting installation must be expressed by photometric values that influence visual performance, visual comfort and non-visual biological effects. The photometric parameters that can be used for specifying, designing and measuring the quality of interior lighting installations range from parameters for illuminance level and illuminance uniformity, wall and ceiling luminance, glare restriction, three-dimensional object and face recognition, modelling, colour appearance and colour rendering. However, international standards and recommendations prepared by recognised lighting standardisation bodies that specify lighting from the point of non-visual biological effects do not yet exist. CIE issued a standard that defines the spectral sensitivity function for the photosensitive retinal ganglion cells in terms of the melanopic irradiance [35]. In a 2019 position statement, CIE proposes to take the non-visual re-

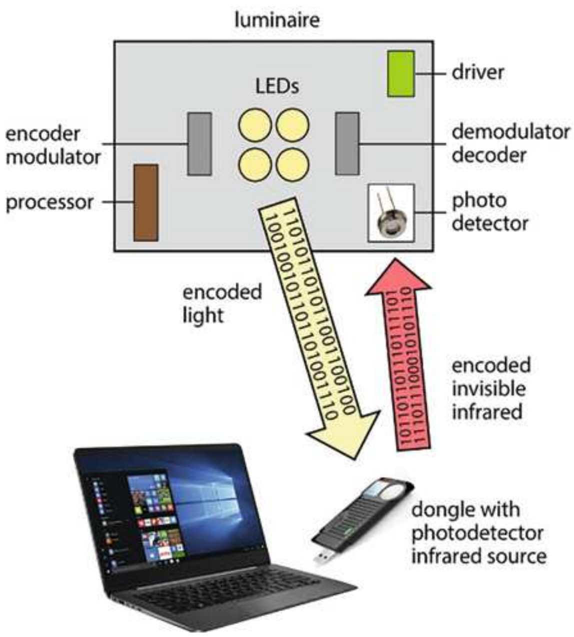

Fig. 21. Bidirectional Li-Fi data communication network with visible light downlink and invisible infrared uplink

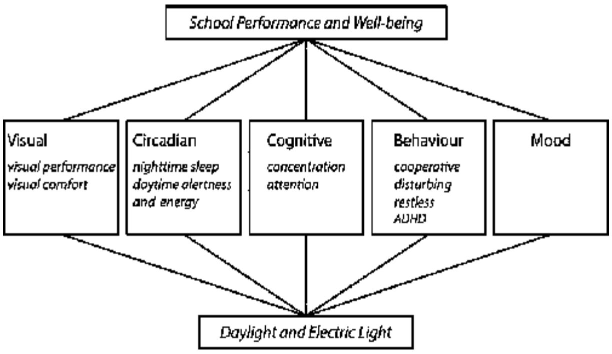

Fig. 22. The relations between lighting effects that together influence school performance and well-being of pupils and students, [66]

sponses to light into account by using the melanopic equivalent daylight (*D65*) illuminance, the melanopic EDI [65]. This unit is recommended to be used in future recommendations for non-visual biological effects.

3.2. Design Aspects

The lighting design process varies with the type of application and with the character of the designer. As far as the technical aspects of the lighting design process are concerned, five steps can be identified that are common to most lighting applications. They are listed, in the sequence of the design process, in Table 5.

With regard of the choice of the lighting system, the advantages of general lighting, localised lighting and their combinations have to be considered, just as the advantages of direct, indirect and combination of direct and indirect lighting. Dynamic lighting scenarios for office and industrial lighting that optimise performance, health and well-being have to be defined. For classroom lighting, dynamic automated lighting with the possibility for the teacher to put the lighting in a concentration or relaxation mode is a possibility. Fig. 22 shows a scheme that shows the relation of most of the beneficial lighting effects on the performance and well-being of the pupils.

For wardrooms and intensive care units in hospitals, lighting that provides a robust and regular circadian rhythm for the patients can result in potential advantages for their recovery. Dynamic lighting in nursing homes for the elderly can provide not only a robust circadian rhythm but also a therapeutic effect for many Alzheimer's patients with regard to their sleep-wake rhythm.

Table 5. The Five Phases of the Lighting Design Process

1. Analysis of the lighting functions
2. Determination of the relevant lighting quality parameters and their values
3. Choice of the lighting and control system
4. Choice of the lamp and luminaire types
5. Determination of the number and positions of the luminaires

Emergency lighting has to be designed to ensure the safety of users and visitors of a building when, in the case of a calamity, the normal lighting fails.

3.3. Calculations and Measurements

The lighting designer has to perform lighting calculations in order to arrive at solutions that satisfy the relevant lighting requirements. Universally applicable computer programs are available for this purpose. The lumen method of calculating the lighting level on the working plane is a simplified "calculation-by-hand" method. It provides inexperienced lighting designers with a tool to learn to understand, for different types of light distribution, the effect the room dimensions and reflectances have on the resulting average horizontal illuminance of the room.

The measurements carried out in connection with interior lighting fall into three categories: those to determine the lamp properties, the luminaire properties and the installation properties. The measurements of the first two categories are mostly carried out in laboratories. They concern the measurement of the luminous flux of lamps and luminaires, the light distribution and light-emitting area of luminaires and the spectral data of lamps.

Field measurements are carried out on new installations to check whether they fulfil the quality specifications, and on installations already longer in use to reveal whether there is a need for maintenance, modification or perhaps replacement. They concern illuminance, luminance and glare measurements. Light-logging devices are used to gather information about the light dose persons are receiving under different circumstances.

Today, with the availability of LEDs with widely different light colours, it is essential that the lighting professional can check the colour properties of light in the field. Fortunately, relatively low-cost

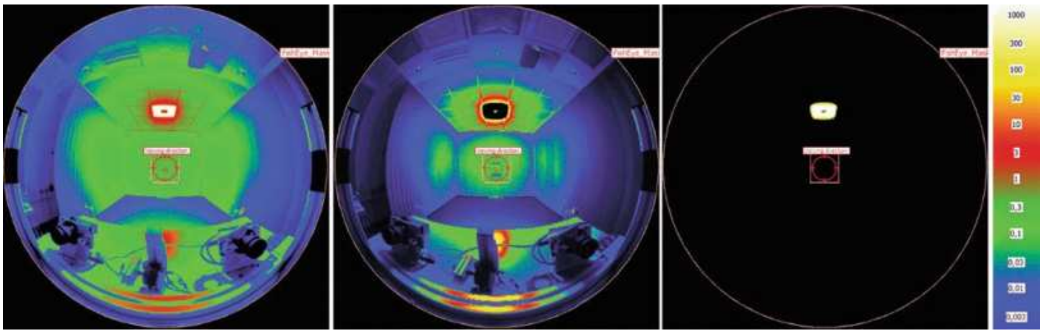

Fig. 23. Luminance mapping to measure UGR; left: map of the whole office; middle: map with the glare source eliminated to determine the background luminance; right: map with the isolated glare source to determine the glare source luminance and light-emitting area; red circles in the centre of the map: viewing direction (photograph: Christoph Schierz)

spectrophotometers, without moving parts (contrary to most laboratory devices), have become available. Most such meters have embedded software that calculates from the measured spectrum all kind of colour characteristics such as chromaticity coordinates x and y, position in any chromaticity diagram, CCT, R_a, R_f and R_g values. These values can be displayed together with the spectrum itself on the meter immediately after the measurement.

For the measurement of the detailed luminances of a lighted scene, luminance mapping technology is more and more used. This technology makes use of CCD cameras. The perspective image of the scene to be measured is projected on the CCD's pixel matrix. The signal of each pixel is proportional to the luminance of the corresponding scene element. Depending on the meter's position and orientation relative to the scene, the perspective image can be converted through complex mathematical calculation software into a plane, non-perspective, image in which each pixel represents a small, same-sized scene area. From a single measurement, the software subsequently calculates the average scene luminance and the luminance uniformities. Cameras with incorporated luminance mapping software are also referred to as imaging luminance measuring devices (ILMDs). Sometimes it is desired to measure glare on location. For this purpose, ILMDs devices can also be used. Fig. 23 shows an example for an office with one single Luminaire.

REFERENCES

1. Van Bommel W.J.M. (2019). Interior Lighting, fundamentals, technology and application// Springer Nature, Switzerland.

2. Donners MAH, Vissenberg MCJM, Geerdinck LM, Van Den Broek-Cools JHF, Buddemeijer-Lock A (2015) A psychophysical model of discomfort glare in both outdoor and indoor applications. In: Proceedings 27th CIE Session, Manchester, pp. 1602–1611.

3. Safdar M., Luo M.R., Mughal M.F., Kuai S., Yang Y., Fu L., Zhu X. (2018). A neural response-based model to predict discomfort glare from luminance image// Lighting Res. Technol., # 50, pp. 416–428.

4. Scheir G.H., Hanselaer P., Ryckaert W.R. (2019). Pupillary light reflex, receptive field mechanism and correction for retinal position for the assessment of visual discomfort// Lighting Res. Technol., Vol. 51, #2, pp. 291–303.

5. Scheir G.H., Donners M., Geerdinck L.M., Vissenberg M.C.J.M., Hanselaer P., Ryckaert W.R. (2018). A psychophysical model for visual discomfort based on receptive fields// Lighting Res. Technol. # 50, pp. 205–217.

6. IES (2018), Publication IES TM-30–18: IES method for evaluating light source color rendition. IES, New York.

7. Smet K., Ryckaert W.R., Pointer M.R., Deconinck G., Hanselaar P. (2011). Correlation between colour quality metric predictions and visual appreciation of light sources// Opt. Exp., #19, pp. 8151–8166.

8. Houser K.W., Wei M., David A., Kramer M.R., Shen X.S. (2013) Review of measures for light-source colour rendition and considerations for a two-measure system for characterizing colour rendition// Opt. Exp. #21, pp. 10393–10411.

9. Gu H.T., Luo M.R., Liu X.Y. (2017) Testing different colour rendering metrics using colour difference data// Lighting Res. Technol. #49, pp. 539–560.

10. Teunissen C., van der Heijden F.H.F.W., Poort S.H.M., de Beer E. (2017). Characterising user preference for white LED light sources with CIE colour rendering index combined with a relative gamut area index// Lighting Res. Technol. # 49, pp. 461–480.

11. CIE Publication 224:2017: CIE2017, Colour fidelity index for accurate scientific use, Vienna.

12. Weston H.C. (1953). The relation between illumination and visual performance// Reprint IHRB Rep.

No. 87 (1945) and Joint Rep. (1935). Medical Research Council, HMSO, London.

13. Weston H.C. (1961). Rationally recommended illuminance levels// Trans. Illum. Eng. Soc. (Lond), Vol. 26, #1, pp. 1–16.

14. Muck E., Bodmann H.W. (1961) Die Bedeutung des Beleuchtungsniveaus bei praktische Sehtätigkeit// Lichttechnik, #13, pp. 502–507.

15. Rea M.S. (1981). Visual performance with realistic methods of changing contrast// J. Illum. Eng. Soc. Vol. 10, #3, pp. 164–177.

16. Rea M.S. (1986). Toward a model of visual performance: foundations and data// J. Illum. Eng. Soc., #15, pp. 41–57.

17. Eklund N.H., Boyce P.R., Simpson S.N. (2001) Lighting and sustained performance: modelling data-entry task performance// J Illum. Eng. Soc. #30, pp. 126–141.

18. CIE (2002a) International Commission on Illumination Publication 145:2002 The correlation of models for vision and visual performance. CIE, Vienna.

19. Houser K.W. (2014).To use or not to use TM-24 // Leukos, # 10, pp. 57–58.

20. Loe D.L., Mansfield K.P., Rowlands E. (1994) Appearance of lit environment and its relevance in lighting design: experimental study// Lighting Res. Technol., Vol. 26, #3, pp. 119–133.

21. Kirsch R.M. (2014) Lighting quality and energy efficiency in office spaces. Doctoral thesis, Department of Lighting Technology, Technical University, Berlin.

22. Oi N., Mansfield K.P. (2015). Lighting quality: possibility of luminance distribution as its determinant// Proceedings CIE28th Session, Manchester, pp. 1111–1120.

23. Loe D.L. (2016). Light, vision and illumination: the interaction revisited// Light Res. Technol. Vol. 48, pp. 176–189.

24. Cuttle C. (2008): Lighting by design, 2nd edition. Architectural Press, Oxford.

25. Cuttle C. (2010): Towards the third stage of the lighting profession// Lighting Res. Technol., #42, pp. 73–93.

26. Cuttle C. (2018): A fresh approach to interior lighting design: the design objective-direct flux procedure// Lighting Res.Technol., #50, pp. 1142–1163.

27. Mury A.A., Pont S.C., Koenderink J.J. (2009) Representing the light field in finite three-dimensional spaces from sparse discrete samples// Applied Opt., #48, pp. 450–457.

28. Huang A., Sanderson A. (2014) Light field modelling and interpolation using Kriging techniques// Lighting Res. Technol., #46, pp. 219–237.

29. Pont S.C. (2013). Spatial and form-giving qualities of light// In: Albertazzi L. (ed) Handbook of experimental phenomenology: visual perception of shape, space and appearance. Wiley Chichester.

30. Kartashova T., Sekulovski D., De Ridder H., Te Pas S.F., Pont S.C. (2016) The global structure of the visual light field and its relation to the physical light field// J. Vis. Vol. 16, #10, p.9 and

Kartashova T, Te Pas S., Ridder H., Pont S., (2019). Light Shapes: Perception-Based Visualizations of the Global Light Transport// ACM Transactions on Applied Perception, #16, pp. 1–17.

31. Xia L., Pont S.C., Heynderickx I. (2017) Light diffuseness metric part 1: theory// Lighting Res. Technol. #49, pp. 411–427, and Light diffuseness metric part 2: describing, measuring and visualising the light flow and diffuseness in three-dimensional spaces// Lighting Res. Technol. #49, pp. 428–445.

32. International Commission on Illumination CIE Publication 232:2019, Technical report, Discomfort caused by glare from luminaires with non-uniform source luminance, Vienna.

33. Kruithof A.A. (1941). Tubular luminescence lamps for general illumination// Philips Technical Review, Vol. 6, #3, pp. 65–73.

34. Berson DM, Dunn FA, Takao M (2002) Phototransduction by retinal ganglion cells that set the circadian clock// Science, #295, pp. 1070–1073.

35. International Commission on Illumination CIE International Standard CIE026:2018 CIE system for metrology of optical radiation for ipRGC-influenced responses to light, Vienna.

36. Eastman C.I., Boulos Z., Terman M., Campbell S.S., Dijk D.J., Lewy A.J. (1995a) Light treatment for sleep disorders: consensus report. VI. Shift work// J. Biol. Rhythm #10, pp. 157–164.

37. Dumont M., Blais H., Roy J., Paquet J. (2009) Controlled patterns of daytime light exposure improve circadian adjustment in simulated night work// J. Biol. Rhythm, Vol. 24, #5, pp. 427–437.

38. James F.O., Cermakian N., Boivin D.B. (2007) Circadian rhythms of melatonin, cortisol and clock gene expression during simulated night shift work// Sleep, #30, pp. 1427–1436.

39. Folkard S. (2008) Do permanent night workers show circadian adjustment? A review based on the endogenous melatonin rhythm// Chronobiol. Int., #25, pp. 215–222.

40. Boudreau P, Dumont GA, Boivin DB (2013) Circadian adaptation to night shift work influences sleep, performance, mood and the autonomic modulation of the heart. PLoS One 8: e70813.

41. Werner J.S., Schefrin B.E., Bradley A. (2010). Optics and vision of the aging eye// In: Bass M., Enoch J.M., Lakshminarayanan V. (eds) Handbook of optics, Vision and vision optics, Vol III, 3rd edition, McGraw-Hill, New York.

42. Owsley C. (2011). Aging and vision// Vis. Res., #51, pp. 1610–1622.

43. CIE Publication 227:2017, Lighting for older people and people with visual impairment in buildings, Vienna.

44. Rosenthal N.E., Sack D.A., Gillin J.C., Lewy A.J., Goodwin F.K., Davenport Y., Mueller P.S., Newsome D.A., Wehr T.A.(1984). Seasonal affective disorder. A description of the syndrome and preliminary findings with light therapy// Arch. Gen. Psychiatry, Vol. 41, #1, pp. 72–80.

45. Meesters Y., Gordijn M.C.M. (2016). Seasonal affective disorder, winter type: current insights and treatment options// Psychol. Res. Behav. Manag., # 9, pp. 317–327.

46. Van Someren E.J.W., Riemersma-Van Der Lek R.F. (2007). Live to the rhythm, slave to the rhythm// Sleep Medicine Reviews, # 11, pp. 465–484.

47. Hanford N., Figueiro M. (2012) Light therapy and Alzheimer's disease and related dementia: past, present, and future// Journal of Alzheimer's disease Vol. 33, #9, pp. 913–922.

48. Figueiro M.G., Kalsher M., Plitnick B., Rohan C., Rea M.S. (2018) Mood and agitation// SlEEP # 41, pp.A113-A114.

49. Van Someren E.J.W., Kessler A., Mirmiran M., Swaab D.F. (1997). Indirect bright light improves circadian rest-activity rhythm disturbances in demented patients// Biol Psychiatry, # 41, pp. 955–963.

50. IEC61000–4–15:2010 Electromagnetic compatibility (EMC)—Part 4–15: Testing and measurement techniques – flickermeter – functional and design specifications.

51. Perz M., Vogels I.M.L.C., Sekulovski D., Wang L., Tu Y., Heynderickx I.E.J. (2015). Modelling the visibility of the stroboscopic effect occurring in temporally modulated light systems// Lighting Res. Technol., # 47, pp. 281–300.

52. Wang L., Tu Y., Lu L., Perz M., Vogels I.M.L.C., Heynderickx I.E.J. (2015). 50.2: Invited paper: stroboscopic effect of LED lighting// SID Symp. Digest Tech. Paper #46, pp. 754–757.

53. CIE Standard S009:2002. Photobiological safety of lamps and lamp systems, Vienna.

54. Behar-Cohen F, Martinsons C, Viénot F, Zissis G, Barlier-Salsi A, Cesarini JP, Enouf O, Garcia M, Picaud S, Attia D (2011) Light-emitting diodes (LED) for domestic lighting: Any risks for the eye? Progress in Retinal and Eye Research 30:239–257.

55. SCENIHR, 2012. Health effects of artificial light. European Commission, Brussels.

56. Bullough JD, Bierman A, Rea MS (2019) Evaluating the blue-light hazard from solid-state lighting. Int J Occup Saf Ergon. Oct 6:1–10 Epub ahead of print.

57. CIE (2019b): CIE position statement on blue light hazard 2019, Vienna.

58. IEC62717, edition 1.1: 2015, LED modules for general lighting – performance requirements.

59. IES (2008), LM-80–08 Approved method: measuring lumen maintenance of LED light sources.

60. IES (2015), Addendum B for TM-21–11 Projecting long term lumen maintenance of LED light sources.

61. TM-21–11 Projecting long term lumen maintenance of LED light sources.

62. Technical Report CIE051.2–1999 A method of assessing the quality of daylight simulators for colorimetry.

63. ISO (2007), ISO 11664–2:2007)/CIE14–2/E: 2006 Colorimetry – part2: CIE standard illuminants for colorimetry.

64. Technical Report CIE215:2014 CIE standard general sky guide.

65. CIE position statement on non-visual effects of light: Recommending proper light at the proper time, 2nd edition, Vienna.

66. Mott M.S., Robinson D.H., Walden A., Burnette J., Rutherford A.S. (2012). Illuminating the effects of dynamic lighting on student learning// SAGE Open, April-June 2012, pp. 1–9.

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