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On course for better lighting design

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Abstract

The purpose of the paper is to study the use of new metrics of light stimulus instead of traditional photopic luminous efficiency function and light measures, in particular, for spatial brightness. Given new lighting standards, it is essential to extend dynamic lighting methods to circadian lighting. Experimental data have been studied, showing the effects of all photoreceptors (cones, rods, ipRGC) on the light pattern of lighting design, which allows for the practical use and correlation of reliable (objective) measurements of optical radiation and subjective perception by a person. A scenario of circadian lighting of a flat is proposed. The lighting design process is considered, which consists in using alternative metrics, compared to traditional ones, to better describe light measures. The development of lighting design was facilitated by the discovery and study of a new photoreceptor ipRGC, as well as the widespread acceptance of LED light sources with their capabilities in terms of spectrum, energy, and dynamics. The obtained results indicate a better correlation between the measurement results of lighting scenarios and subjective human perception.

Keywords: circadian lighting; dynamic lighting; spatial brightness; lighting design.

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Introduction

Lighting manufacturers and designers have to be sure that their products and designs ensure the claimed benefits. Lighting has undergone significant changes since the beginning of the century. The widespread acceptance of LEDs and a growing awareness of the lighting effects beyond visual perception have transformed the field. The discovery by Berson and colleagues of a novel photoreceptor associated with non-visual responses to light has not only prompted a reconsideration of traditional lighting concepts, but also gave rise to the development of new standards and analytical methods for assessing the receptor properties. The 21st century's lighting technologies are a bridge between research work in such fields as psychology, biology, on the one hand, and architectural lighting, technological development of LED systems, and lighting practice, on the other. The development and use of new metrics of light stimulus is relevant for the lighting community. Despite the availability of more advanced alternatives, some foundational quantities with well-documented limitations are still widely used. These include the photopic luminous efficacy function $V\lambda$, which has been in use for over a century, the CIE 1931 standard colorimetric observer with a 2-degree visual field introduced around 95 years ago, and the colour rendering index (CRI), introduced approximately 50 years ago. As LEDs develop, outdated metrics are an obstacle that modern lighting practice has been tackling, and they contribute to the scientific debate about "proper lighting design". To assess the characteristics of the radiation of light systems by their effect on all photosensitive cells of the eye, the CIE introduced names for five weighted illuminances (α-opic) according to their photopigment name: melanopic (for ipRGC), rhodopic (for rods), cyanopic (for S-cones), chloropic (for M-cones), erythropic (for L-cones) illuminance. Among the metrics proposed by the CIE there is "melanopic lux", which is a term that describes the flux density weighted by the function of the luminous efficiency, the maximum sensitivity of which is at a wavelength of 480 nm and is based on the action of the melanopsin spectrum. Among the metrics that have found their wide application in lighting practice, the following should be noted: R_f – colour accuracy index in addition to the colour rendering index (CRI), R_g – colour coverage, Duv – distance from the black body location, which describes the spectral characteristics of light sources.

The development and use of new metrics, phasing out the predominant use of the photopic luminous efficiency function, make up a new model of lighting design. At the same time, the most critical issue of describing the lighting measures as accurately as possible, which would be adequate for human perception, is being addressed. Considering the technical aspect of lighting design, the uniqueness of characteristics of LEDs for various applications shall be noted, in particular, their wide range, lighting control capability, change the correlated colour temperature, and actual inertialessness.

Methods and findings of the study. Discussions

It is essential to be able to project the brightness of the surrounding spaces. In addition to the amount of light delivered and reflected from the surfaces in the space, the spectrum of light affects the apparent brightness of the scene. Specifically, spaces illuminated by "cool light" sources will appear brighter than those illuminated by "warm white" sources at the same photopic light levels. Managing the apparent luminance of a scene is an important goal of lighting design. Obviously, increasing or decreasing the illuminance on surfaces in the interior of a room will make it appear more or less bright. Similarly, the distribution of light in the space, as well as the values of the reflection coefficients, affect the overall perception of the brightness of the scene. According to the results of some empirical studies, the brightness of illuminated objects depends on the correlated colour temperature of the illuminants. Thus, for example, a room illuminated by a daylight source will appear brighter than one illuminated at the same photopic levels by an incandescent lamp.

Despite the proven usefulness of CIE photometry and colorimetry, many studies have shown that lumen-based metrics are not fully compatible with human perception of brightness. Early projects for recommended illuminance levels were close to the effective performance of typical visual tasks, but with the advent of fluorescent lamps these levels have been reaching their current values despite the widespread acceptance of technologies that made visual tasks easier. Nevertheless, visibility is cited as a fundamental purpose of lighting. This is clearly stated in the IESNA document "Guidelines for the Design of Quality Lighting for People and Buildings", which opens with the following: "The objective of visibility is essential to lighting design; lighting exists to provide vision." This view deserves some study (see Fig. 1).

Fig. 1 [1] shows that the typical task of reading black type on white paper for a 25-year-old subject with normal vision requires just 20 lux to provide the relative visual performance (RVP) criterion, the value of which is 0.78. This value is generally accepted as the highest practical RVP level for lighting applications. It can be seen that the font size shall be reduced to 6 pt for the required illuminance to exceed 100 lux or alternatively reduced to 10 pt while printed on dark paper, which has the double effect of reducing background brightness and task contrast. However, this value of 100 lux is far from the levels normally expected for applications where reading tasks predominate, which are typically in the mid-range of 300 to 500 lux, and it is clear that such levels shall be justified based on visual performance only if any users have visual defects, or if they are required to read very small type with very low contrast against a background of low reflectivity. We are now faced with the examples of recommended illuminance levels that far exceed the levels required to satisfy visual performance needs, while users complain of the "cave effect" and the lack of taste and gloomy workplaces. In the middle of the last century, a new design trend sprang up. In the United States, this was adopted by stage lighting designers, who established strong links with some leading architects of the time and brought the magic of the theatre into architecture. In the UK, another significant new approach was introduced, largely attributed to Y.M. Waldram, who is the creator of the Designed Appearance Method [2]. Although the design philosophies may have differed, these lighting designers saw the purpose of lighting as quite different from the approach to visibility – for them, it was a question of how lighting could be used to affect the overall view of the room, especially interior spaces. The decision that the purpose of lighting is to provide visibility or perception continues to divide lighting professionals into different camps who read different publications, attend different conferences and join different professional communities. To make matters worse, the gap is widening, while lighting regulations developed with the best intentions – resource management, environmental protection and ageing – follow the pattern set by the "visibility" camp since the illuminance is assessed in terms of illuminance values measured at "visual task planes", which is almost interpreted as referring to the horizontal work plane (HWP). The current European standard EN12464-1 and other lighting design standards are based on the conception of providing the minimum value of illuminance on the HWP.

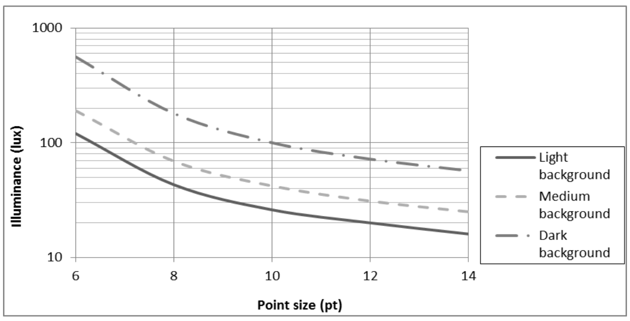

Fig. 1. Visual characterization (RVP) versus illuminance for various reading conditions [1]

This situation is a sentence for the "perception" camp, for whom the essence of lighting design is to develop light distributions appropriate to particular locations and activities. They contrast light and darkness to influence the overall look of a space and to create local accents and modelling that may come from any direction. The basic standards for brightness and uniformity of the work plane fall short of their intended purpose and, ultimately, fail to support the objectives of either perspective. There is a real need for a completely new approach to defining the basis of lighting practice.

Previously, suggestions were made to replace the specification of horizontal work plane illuminance with a brightness-based lighting metric, most notably the "perceptual design method", followed more recently by "spatial brightness", or "scene brightness". Typically, these assume a fixed viewing position and viewing direction, allowing the field of view to be specified as the distribution of brightness, except for the scene brightness, for which it is given by the illuminance measured at the eye normal to the viewing direction. It is essential to be able to project the brightness of an interior space. Despite the proven usefulness of photometry and colorimetry of the CIE, according to the results of many studies, lumen-based metrics are not fully capable of capturing human perceptions of brightness. One key component of lighting quality is how spatial brightness is perceived. According to the IES Visual Effects of Lamp Spectral Distribution Committee, spatial brightness refers to the visual impression of the overall intensity of ambient light in a given setting, such as a room or a street. This ambient illumination contributes to the atmosphere and supports broader visual tasks like safe movement and communication. The perception involves a general visual response that includes much of the visual field beyond the central focus (fovea). It can be experienced either while physically present in the space or when viewing it from a distance, provided it occupies a significant portion of the visual field. Essentially, spatial brightness is not directly linked to the luminance of specific objects or surfaces, though these elements can influence the overall perception.

The possibility to control the apparent brightness of a scene is of utmost importance in terms of lighting design. The spectral sensitivity of the scene brightness cannot be determined for photopic quantities based on the photopic luminous efficacy $V(\lambda)$. The photopic luminous efficacy function was conceived and later described as the spectral sensitivity of the human eye to electromagnetic radiation. It was derived largely from experiments using flicker photometry. The numerous studies of $V(\lambda)$ conducted since 1924 confirmed that $V(\lambda)$ reflects the combined spectral sensitivities of the L- and M-cones as they feed the retinal magnocellular channel. These early studies of human subjects used their fovea for 2 degrees' visual field.

The fovea is a small area of the retina that corresponds to what is called central vision and has the highest density of photoreceptors, which provide the highest spatial resolution (i.e., acuity). In reality, only cone photoreceptors are found in the fovea, and the majority are L-cones and M-cones. The central fovea has almost no S-cones. A representation of light based solely on $V(\lambda)$ will not provide reliable visual effects for many applications. Visual perception is not the only monolithic process that provides the brain with a photopically weighted picture of the physical environment. Instead, multiple neural pathways link the retina to the brain, each serving distinct roles. Together, they contribute to a unified perception of the surrounding environment. These pathways span the light spectrum by various combinations of the same photoreceptor types in unique ways. Crucially, if light is assessed solely through the lens of the photopic luminous efficiency function, one fails to capture its full impact since it has an impact on diverse neural circuits that shape our overall perception of the physical world.

In [3], five action spectra of all five photoreceptors is proposed. Given these considerations, the melanopic action spectrum has become the most commonly applied tool among researchers and lighting designers. CIE [4] proposed "α-opic" approach to determine values for each type of photoreceptors based on irradiance and illuminance. One of the significant photoreceptors characteristics is α-opic daylight $D65$ efficacy ratio (DER) $\gamma_{\alpha v}^{D65}$, which can be evaluated as the ratio of the α-opic efficacy of luminous radiation (ELR) of the test source, $K_{\alpha v}$ to the α-opic ELR of daylight $D65$, $K_{\alpha v}^{D65}$:

$$\gamma_{\alpha v}^{D65} = K_{\alpha v} \times (K_{\alpha v}^{D65})^{-1}. \qquad (1)$$

According to [3], α-opic can be replaced by sc for S-cones values (sc-DER, sc-ELR and other), mc for M-cones values, lc for L-cones values, rh for rhodes' values, and mel for ipRGCs values.

Thus, the publication of CIE S026/E:2018 and the increasing awareness of photoreceptor interaction mechanisms overcome the difficulties in assessing the involvement of ipRGCs in brightness perception and the extent of their contribution. In recent years, some researchers have proposed a spatial brightness model that includes melanopic illuminance or related quantities that use coefficients and exponents to correlate with the magnitude of the impact of melanopic light illuminance compared to photopic illuminance (Khanh et al. [5]). The study has demonstrated that not only the L+M component, but also S-cones and ipRGCs matter, even though its size is reduced. Thus, a visual scaled brightness model has been proposed that is based on optimizing the obtained data using not only illuminance, but also S-cones and ipRGCs. In the study by Rea et al. [6], both subjective evaluations and radiometric measurements were used to refine an earlier model of scene brightness. This enhanced model was intended to improve predictions of perceived brightness in indoor environments lit to varying levels by "white" light sources with different correlated colour temperatures. However, these models have yet to demonstrate sufficient external validity to support their practical implementation validity that would allow for widespread implementation in practice. For example, the studies that included various types of lamps or different correlated colour temperature (CCT) have generally concluded that spatial brightness is affected by these factors, but this characterization bears a limited resemblance to the spectral power distribution. Since all measurements proposed for predicting spatial brightness are simplifications derived from the SPD of light sources, there is significant potential for confounding variables, leading to incorrect estimates of causal effects. Simple metrics cannot account for complex differences in SPD.

Recent studies have advanced our understanding of the effects of ipRGCs, S-cones, and colour on spatial brightness. Following the publication of CIE S026/E:2018, researchers have been using updated melanopic metrics (such as the effective mel-DER) to better quantify non-visual light effects. Similarly, there is an increasing understanding of how ipRGCs contribute to brightness perception, along with a clearer sense of the strength of their influence. Among the proposed spatial brightness models that include melanopic illuminance and related quantities, the work of Khann et al. [5] is worth noting. However, the proposed models consider a limited number of SPDs, which have little flexibility in targeting different spectral quantities based on metamers. It is difficult to manipulate the SPD change to identify the cause of the effect. By the mid-1990s, models were proposed that used S-cone responses to account for the apparent effects of short-wavelength content on spatial brightness. Fotios and Levermore [7] studied several alternative models, including one based on the ratio of S-cone illuminance to photopic illuminance. Thus, in the earlier model of Rea [6] Khanh [5] included S-cones in the contributions of ipRGCs. Just as the models that include conditions for ipRGC contributions, much of the experimental data is limited by the type and number of stimuli. While direct links between melanopsin and brightness perception have already been found, the case for S-cones remain not so clear. Bullough [8] noted that "although there is little physiological evidence that an additive combination of photopic and S-cone signals plays a role in visual processing, the spectral sensitivity implied by such a combination can be approximated (provided that the relative coefficients are appropriately adjusted) by the algebraic combination of the photopic brightness channel with the spectrally opposite blue-yellow [B-Y, S-cones (L+M)-cones] colour channel."

Regarding the effects of CCT (and chromaticity in a broader sense) on spatial brightness perception, the evidence is ambiguous. There are several studies [9, 10] that report an increase in spatial brightness with increasing CCT, others find no such increase [11, 12], and at most one shows the opposite [13]. In certain experiments, CCT was the sole descriptor of the spectral power distribution (SPD). However, CCT is a relatively imprecise measure, and other spectrally derived parameters (such as colour rendering or Duv) can vary considerably even when the CCT remains constant. Without these additional variables being monitored, studies that rely on CCT as the primary independent factor are unlikely to yield any results with strong external validity. Another significant consideration is that CCT and other measurements related to short-wave content, such as mel-DER and especially sc-DER, are correlated (p-correlation coefficient). From various theoretical perspectives SPDs used in recent studies [14], *r`* was 0.49 between CCT and mel-DER, and 0.88 between CCT and sc-DER. If we confine ourselves to the group of SPDs with $-0.0002 \leqslant \text{Duv} \leqslant 0.00002$, *r* increases to 0.96. This relation suggests that altering the CCT will typically result in a change in sc-DER, unless spectral characteristics are carefully monitored. As a consequence, it becomes difficult to attribute changes in spatial brightness solely to variations in CCT. The connection between colour rendering and spatial brightness perception has been studied using metrics based on colour gamut area. However, colour gamut is conceptually average and increasing or decreasing can be achieved by changing the perceived colour purity of various colour tones in different ways (i.e., having different colour gamut contours [15]) – there are also functional differences between outdated metrics, such as the colour discrimination index, and modern colour gamut measurements [16].

The understanding and quantification of colour rendering have considerably advanced over the past decade. Modern methods such as ANSI/IES TM-30 have facilitated the analysis of colour rendering beyond average colour accuracy and colour gamut, such as colour gamut contour and colour purity shift [15] – variables whose effects on spatial brightness have not been thoroughly studied. Another important area of research focuses on colour rendering and the Hunt effect, showing how colour rendering, specifically increases in red colour purity – can counteract the reduction in perceived colour content (colourfulness) triggered by a decrease in light intensity [17]. The effects of antagonistic channels in spatial brightness perception have received little attention in recent studies, with greater emphasis placed on alternative factors. In this context, the study by Wei et al. [17] should be noted, in which the difference in opponent signals and their contribution to the difference in perception of two stimuli are studied. In [8], it is described how S-cone burn effects are driven by the blue-yellow channel more than the S-cone does itself, providing direct input along the achromatic channel.

The inclusion of scopic values in the brightness model may address the physiological mechanism by which the chromatic component influences the perception of spatial brightness. It is worth noting the substantial study by Royer M., Abboushi B., Rodrigues-Feo Bermudes E. [18] on the perception of spatial brightness and spectral power distribution, which has been implemented in many ways. In fact, this is the first study in which illuminance, chromaticity (CCT and Duv), α-opic values (sc-DER and mel-DER), and colour rendering (R_f, R_g) are systematically varied. The change between seven different factors results in a significantly constrained spectral power distribution, as well as it underpins the study of the relative magnitudes of the effect. Even with a partial factorial design, this required the evaluation of 60 different spectral power distributions, which are most widely represented in spatial brightness studies to date. The room, similar to an office, was illuminated with 60 different lighting conditions that systematically varied with illuminances of 250 lux and 500 lux, chromaticity and CCT of 3500 K and 3850 K, and Duv of 0.006 and 0.000, sc-DER of 0.49 and 0.58, mel-DER of 0.33 to 0.76, colour rendering accuracy with CRI from 80 to 90, and R_g of 0.94 to 110. The colour rendering and illuminance ranges represent typical conditions for architectural interiors. Using a scale from 1 to 8, 32 participants rated each stimulus on the scales of bright-dark, warm-cold, natural-distorted, bright-dim, and like-dislike. The results confirm that spatial brightness perception can be reliably evaluated.

Dynamic circadian lighting

The development and wide acceptance of dynamic LED-based lighting systems and their effects on human circadian rhythms (non-visual effects, such as mood, cheerful circadian rhythms and others) have identified the issues in terms of the assessment of circadian effects. For example, time, duration of light exposure and previous light history, i.e. light, received before the period under consideration, influences circadian effects, not just intensity and spectrum. An improved dynamic lighting design scenario for residential buildings shall promote health by synchronizing light with the activities and circadian rhythms of the occupants over a 24-hour natural cycle. The created circadian lighting system shall also refer to the natural day-night rhythm cycles, acting on the CCT and lighting levels. Lighting, when aligned with established findings, shall serve as a daytime stimulant in frequently occupied spaces such as living rooms and stairwells. Its purpose is to activate both physiological and emotional responses, thereby enhancing cognitive performance and supporting residents in engaging more effectively in social or personal activities. In contrast, the lighting design shall be a non-stimulating factor during the evening and at night, especially in areas used for watching TV or reading and in the bedroom. This system, which implements the lighting scenario, shall change automatically according to the time that follows from the presented program, which is again set at 00:00. The system is also designed with flexibility in mind, enabling users to manually operate it via a user-friendly interface that provides access to three preset modes suited for different tasks. Fig. 2 shows the variation of STG depending on time for four designer lighting programs.

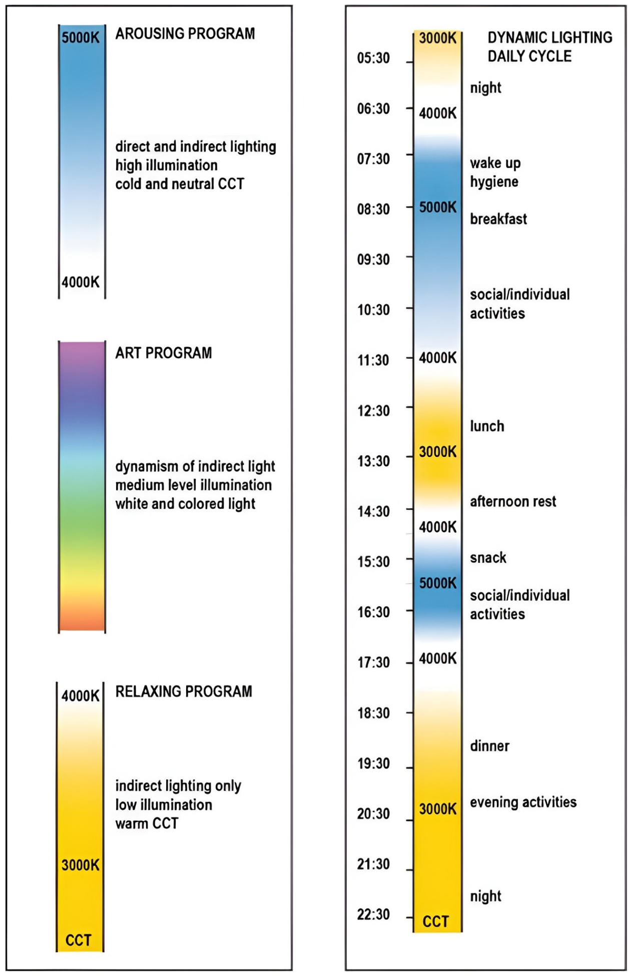

Fig. 2. Four designed lighting programs

On the right, there is a diagram of the automatic adjustment program, while on the left, there are diagrams of the programs that are selected by the user according to specific activities. To meet the aforementioned requirements, the system generates dynamic lighting that evolves over time and adapts to various activity types. This includes modulation of light flux, CCT, and the balance between direct and indirect illumination. Based on the analysis of user activities and the spatial characteristics of the designated areas, the lighting system incorporates the following core principles: more light in the morning and during active activities that require a higher level of attention and concentration; CCT shall be colder in the morning and for activities that require higher cognitive performance (Stimulating, ART, Relaxation and Periodic programs). The periodic ones, within 24 hours of the automatic lighting program, are to facilitate circadian phasing. This includes dynamic light in the diurnal cycle with varying CCT in the range of 3000–5000 K.

Stimulating Program: this mode generates lighting designed to enhance concentration by providing high illuminance levels combined with cool to neutral white CCT, fostering alertness and cognitive engagement.

ART program: it is the lighting that reduces monotony and attention through the dynamic nature of indirect lighting, with medium levels of illumination, including the integration of coloured lighting, in accordance with the principles of the theory of attention reconstruction. Relaxation program: it is comfortable indirect lighting only with low levels of illumination and CCT of 3000 K. The integration of presence sensors and ambient daylight enables energy savings by allowing the lighting system to dynamically adjust based on occupant activity and the availability of natural light. The 24-hour automatic dynamic lighting program is designed according to the types of activities, considered for a person in three places: bedroom (see Fig. 3), dining room (see Fig. 4), and living room (see Fig. 5).

In the bedroom, the importance of lighting with a CCT of 5000 K is considered to stimulate the circadian system in the early morning and immediately after sleep, to facilitate awakening and correct timing of the circadian cycle. At the same time, evening lighting characterized by low CCT promotes relaxation and helps prevent disruption of the circadian rhythm. The system operates across four illumination levels on the floor, with CCT settings aligned to the activity planning and responsive to both occupancy sensors and ambient daylight conditions (see Fig. 3).

In the dining room, four stages of lighting are planned for breakfast, lunch, dinner, and dinner (see Fig. 4).

The lighting level guaranteed at the tables is by default 260 lux, with indirect lighting only, but it can

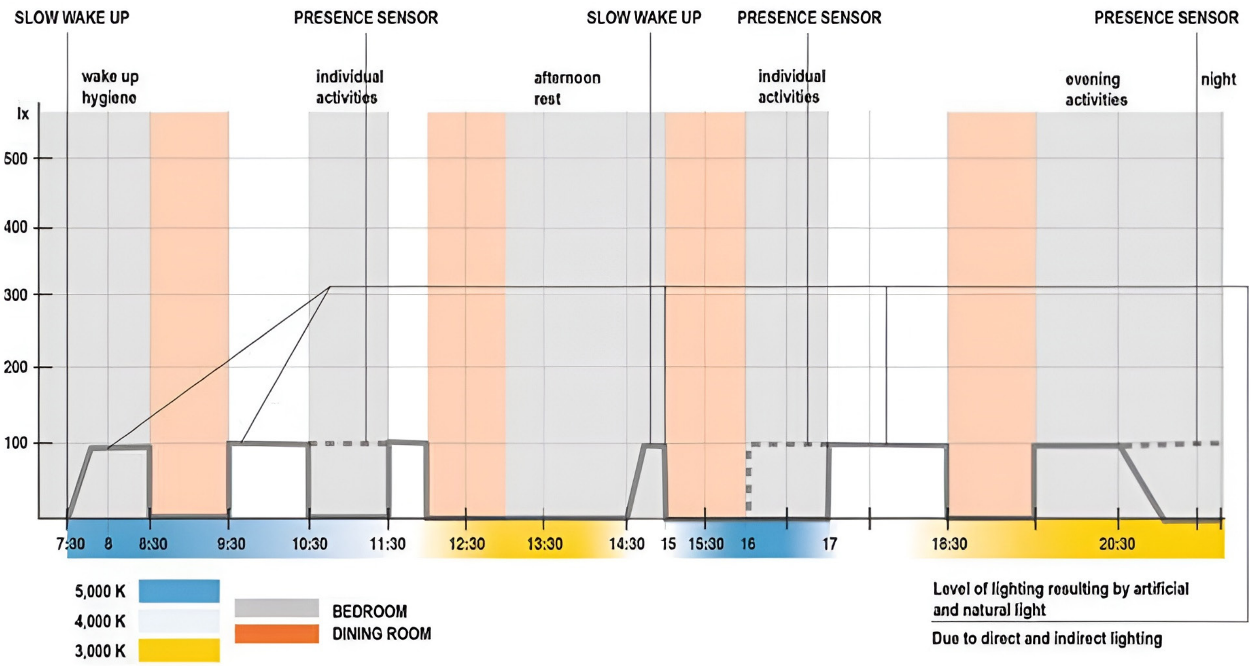

Fig. 3. Lighting scheme applied to the bedroom

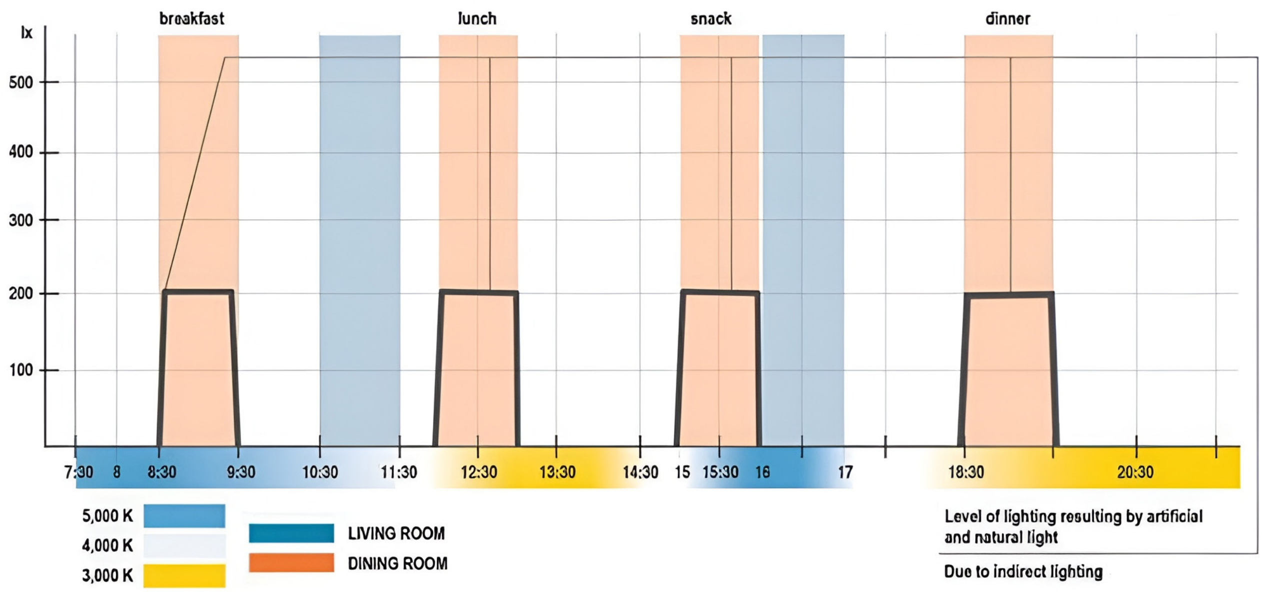

Fig. 4. Lighting scheme applied to the dining room

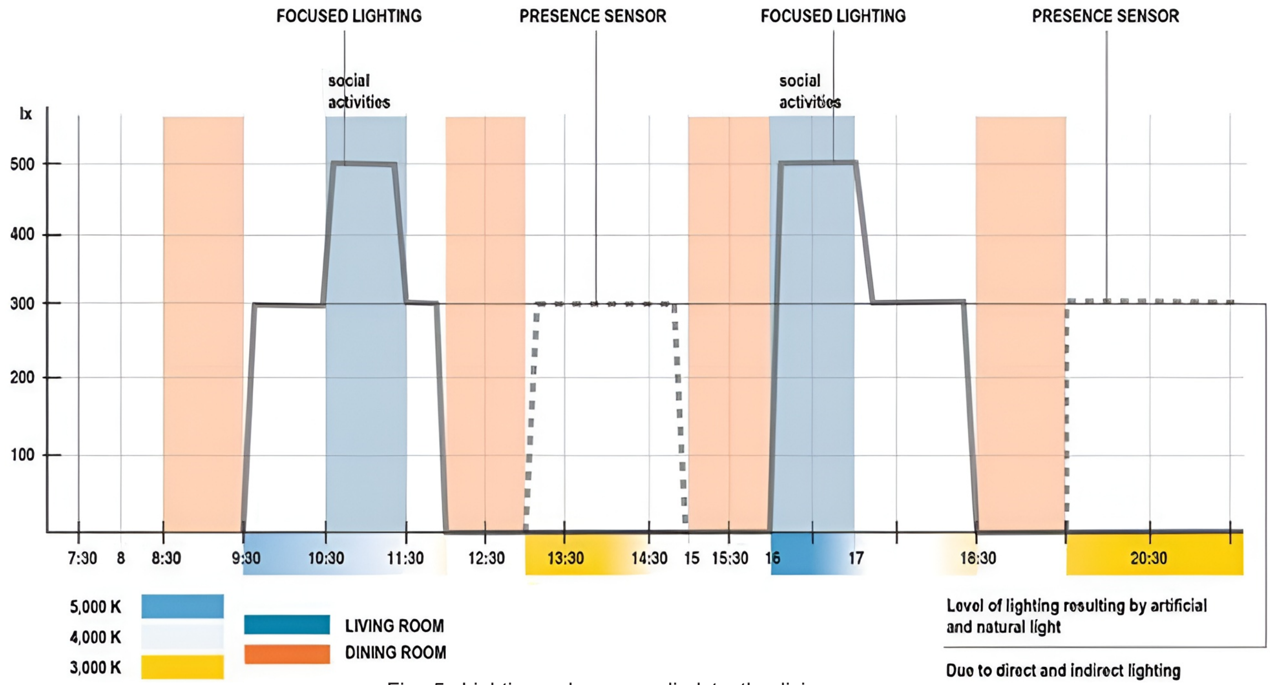

Fig. 5. Lighting scheme applied to the living room

be increased manually to 400 lux, also activating diffuse direct lighting. CCT is high during breakfast and dinner. Simultaneously, it is low during lunch and dinner times, respectively, to perceive the relaxation phases after morning activity and before night sleep. Fig. 4 presents the lighting scheme for a dining room and shows the illuminance levels on the tables, as well as the CCT as determined by the activity plan.

Fig. 5 illustrates the illuminance levels on the tables and CCT as determined by the activity plan and the presence of the sensors.

In the living room, two peak illumination periods are scheduled – mid-morning and afternoon – to support social interaction, reading, and cognitive engagement. In these conditions, there is always both direct and indirect focused lighting with values even exceeding 500 lux. The presence sensors activate the lighting at 300 lux even at unscheduled times, after lunch and after dinner, in case of user presence, while still maintaining low CCT.

The lighting programs are activated manually, are effective for 2 hours, returning to the automatic program and are reset in any case at 00:00. The excitation program provides a high CCT of 5000 K, high illuminance, greater than 500 lux, both with indirect and direct lighting components. Over time, the CCT and illuminance are reduced to 4000 K, 300 lux, respectively. The relaxation program starts from the end conditions of the excitation program to further reduce the CCT to 3000 K and the illuminance to 200 lux. Finally, the ART program uses intermediate levels of illumination in the range of 200–300 lux with white light, both direct and indirect, and the addition of dynamic coloured indirect light to slowly animate the spectrum with colour hues, thereby facilitating recovery from mental fatigue.

Conclusions

Much of the history of the science of lighting and the art of lighting design is the reconciliation of the use of objective measurements of optical radiation with the prediction of subjective perception. The use of traditional metrics of photometry and colorimetry of CIE systems in measuring light stimuli does not appear equally bright to observers in perception, which is a common flaw in traditional lighting design. Modern advanced alternative metrics have been developed to better match human visual perception and measure values of light stimulus. There is sufficient irrefutable evidence that cones, rods, and ipRGCs interact in a complex way to create a light picture in the human brain. However, the model of this interaction is unknown due to its complexity and many unknown factors. Thus, there is no complete scientific explanation of the interaction of photoreceptors.

Nevertheless, amassed experimental data and ongoing studies make it possible to recommend practical use by lighting designers. What should be noted is how significantly the so-called integrated lighting affects the practices of lighting design of LED technologies and new lighting standards. Dynamic lighting is one of the new trends in lighting studies, which has become extremely relevant due to the non-visual impact of light on the human body. The proper levels of lighting at the right time can increase the well-being and efficiency of employees. Lighting design, together with smart devices, provides both comfortable lighting and energy savings.

На шляху до кращого дизайну освітлення

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Анотація

Виробники та дизайнери освітлення мають бути впевнені, що їхні продукти та конструкції досягають заявлених переваг.

Метою роботи є дослідження використання нових метрик світлового стимулу, на відміну від традиційної функції фотопічної світлової ефективності та світлових характеристик, зокрема просторової яскравості. Враховуючи нову парадигму освітлення, важливо поширити динамічні методи освітлення на циркадне освітлення. Були вивчені експериментальні дані, що показують вплив усіх фоторецепторів (колбочок, паличок, ipRGC) на світлову картину проєктування освітлення, що дозволяє практично використовувати та координувати об'єктивні вимірювання оптичного випромінювання та суб'єктивного сприйняття людиною. Запропоновано сценарій циркадного освітлення квартири. Розглянуто процес проєктування освітлення, який полягає у використанні альтернативних метрик, порівняно з традиційними, для кращого опису світлових характеристик. Розвитку дизайну освітлення сприяло відкриття та вивчення нового фоторецептора ipRGC, а також широке впровадження світлодіодних джерел світла з їхніми можливостями в спектральному, енергетичному та динамічному сенсах. Отримані результати свідчать про кращу відповідність між результатами вимірювання сценаріїв освітлення та суб'єктивним сприйняттям людиною.

Використання традиційних метрик фотометрії та колориметрії систем CIE для вимірювання світлових стимулів не здається спостерігачам однаково яскравим у сприйнятті, що є поширеним недоліком традиційного світлодизайну. Були розроблені сучасні вдосконалені альтернативні метрики для кращого узгодження зорового сприйняття людини та вимірювання значень світлових стимулів.

Розглядаючи технічний аспект світлотехнічного дизайну, слід відзначити унікальність характеристик світлодіодів для реалізації різних можливостей: їхній широкий діапазон, можливість керувати освітленням, змінювати корельовану колірну температуру, фактичну безінерційність.

Ключові слова: циркадне освітлення; динамічне освітлення; просторова яскравість; дизайн освітлення.

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