Light & Engineering
Vol. 27, No. 5, pp. 15–21, 2019 *https://doi.org/10.33383/2019-010*

LUMINOUS ENVIRONMENT AND THE PERCEIVED ENVIRONMENT[1]

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ABSTRACT

In lighting design, the main concept is to achieve a healthy environment, which addresses energy efficiency, cost, maintenance, and quality. User-friendly lighting systems shall be adopted to architecture and interior architecture. User control over the lighting system is important, by dimming or increasing light output, by changing the colour of the light sets the inner atmosphere and affects user mood. Standards and codes on lighting shall also be evaluated by means of these topics. The paper aims to analyse how the luminous environment is affective on the perceived environment. Hence, a series of experimental studies and recent research will be evaluated in regard to understanding and designing luminous environment.

Keywords: luminous environment, space perception, lighting standards, indoor lighting

1. INTRODUCTION

Lighting has a route from the luminous environment to the perceived environment, which covers many issues regarding lighting quality and quantity. By referring to the quotes by Cuttle (2003), the luminous environment is transformed into the retinal image, which is the stimulus for the visual process that provides information to enable the perceptual process to recognize objects and surfaces, which form the visual basis for the perceived environment [1].

This statement underlines the importance of measurable items such as the average illuminance on the horizontal or the vertical surface, or the luminance distribution on the wall surface, which lead to simple perceptions. However, the response to the immediate environment covers the non-visual effects of lighting as well. These effects can be grouped as higher-order perceptions [1]; they are the responses of long-term impressions (after spending a certain time in an environment). This process is highly dependent on our knowledge, background, experiences. In the studies, correlation methods are extensively used in order to define the effect of luminous environment on the perception of luminance, colour appearance, and illuminance.

The lighting design approach, which is based on the application of the European Standards such as EN12464–1 [2], shall also be discussed by means of the above issues, regarding non-visual effects of lighting. The critical components in visual comfort: illuminance, luminance, and the spectrum of the light sources are needed to be discussed by means of their interaction with perception, even human health [3]. The paper analyses recent studies and research on designing a luminous environment with respect to the perceived environment.

[1] The editors received several reviews of this publication, two of them positive, one reasonably negative. Nevertheless, the article is published because the issues of visual comfort, which have a long history of research and the non-visual effects of light, studied recently, in modern concepts require a unified approach to the design of lighting systems.

2. VALIDATING VISUAL COMFORT AND DEFINING EMOTIONAL SPACE

The method involves establishing a relationship between subjective judgments and light measurement. In these studies, the criticism of the accuracy of stimulation arises from the case of using scale models and/or computer-aided research methods, which are named as "abstract conditions". Flynn et al [4, 5] had important findings in the sense that they used real interiors and participants. Individual rating scales, which were related to each dimension (perceptual clarity, spaciousness, formality, spatial complexity, evaluative) revealed how lighting design influences space perception. They also evaluated the findings in the three-dimensional space derived from the MDS (multidimensional scaling) analysis. In 1979, Hawkes et al [6] studied a series of lighting installations and developed a map, which shows the location of the types of office lighting on two dimensions, interest and luminance, identified by factor analysis. They concluded on equal preference areas in regard to lighting installations.

There are similar studies, which try to evaluate the effect of the luminous environment on the perceived environment. In 1999, in the study conducted by Manav and Yener [7], 174 undergraduate students evaluated the impression of clarity, spaciousness, relaxation, privacy, pleasantness, and order (the subjective terms on which lighting design is a dominating factor). In a room where no daylight was available, cove lighting was supplied by fluorescent tubes (5400 K) and E_{av} = 270 lx, spaciousness and visual clarity was satisfied. Uplighting was preferred for the impressions of pleasantness, privacy, and relaxation, which was supplied by tungsten filament lamps with E_{av} = 110 lx. Wall washing was satisfied by fluorescent tubes (5400 K), E_{av} = 300 lx, and this system improved the impressions of visual clarity and order. Participants reported more positive feeling under warm light. However, in the study, no special question regarding the colour appearance of the surrounding objects/items was evaluated.

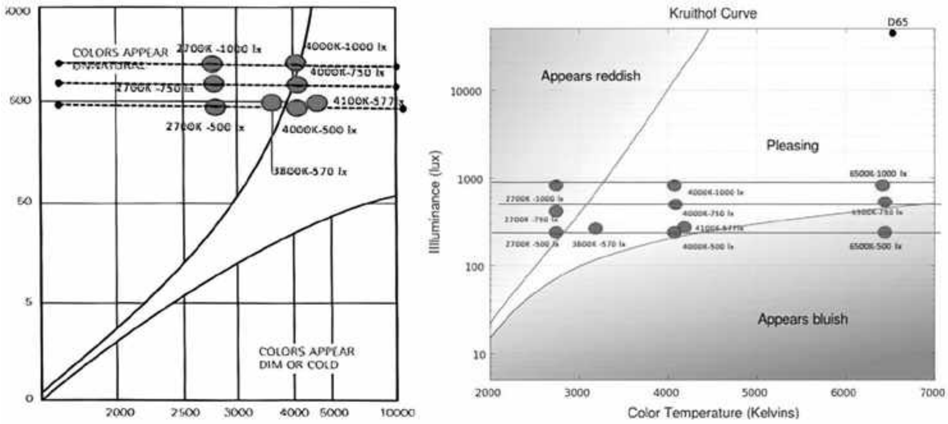
In a series of studies conducted by Manav [8], subjective impressions in regard to colour temperature and illuminance, 2700 K and 4000 K colour temperature for 500–750–1000 lx, were tested. The most suitable lighting scenario(s) were investigated in the study for offices. The results suggest that a change in colour temperature and illuminance has affected the visual appeal of that space. These findings are compared to Kruithof's curve (1941) in Fig. 1a [11] and Kruithof's curve (revised version) in Fig.1b. In both of the curves, 4000 K was better with respect to 2700 K for three of the illuminance levels: 500, 750, and 1000 lx. In the study, 4000 K was preferred to 2700 K for comfort and spaciousness, while 2700 K was suggested for relaxation, luminance and saturation evaluation.

While discussing space perception, the problem shall be approached by energy efficiency, the power of the electrical lighting system, as well as the emotional side, the atmosphere of the space. An experimental study was conducted for this purpose in [9]. In the study, the energy performance (quantitative data) and visual comfort (qualitative data) of tubular LED lamps versus tubular fluorescent lamps were reported. Technical data for tubular fluorescent lamps were as follows: 36 W, 3300 lm, 92 lm/W, 3800 K correlated colour temperature, and 570 lx (the maintained illuminance level on the working surface). Technical data for tubular LED lamps were: 20 W, 1600 lm, 80 lm/W, 4100 K colour temperature, and 577 lx (the maintained illuminance on the working surface). The space perception was evaluated by the following adjectives: spaciousness, wide, airy, and rested (relaxation). The responses were compared under both of the lamp types by SPSS17 statistical program, no significant differences were found by means of quantitative and qualitative data.

Fotios argued on the revised Kruithof's graph by empirical data [10]. He discusses that Kruithof is widely cited as a design rule and has been the focus of many experimental studies, however after 1990, in regard to the advances of the new technology, many empirical data are against his rules. The pleasing conditions are satisfied by avoiding low illuminance and do not favour any colour temperature.

In the present study, two curves, which refer to Kruithof's study, are discussed. Results of some experimental studies, which were conducted by the author and her colleagues, were marked on the graphs. It is seen that there are differences between them such as: 3800 K – 570 lx corresponds to positive subjective impressions according to the above study, it is under "pleasing" region according to the revised Kruithof's curve in Fig. 1b, however it is under "colours appear dim or cold" according to the Kruithof (1941) curve in Fig. 1a.

Similarly, when the other findings in the study conducted by Manav et al [7–9] are plotted



a) *b)*

Fig. 1. a) Evaluating visual comfort conditions by Kruithof's curve (1941); b) Kruithof's curve [11]

on Kruithof's curve, there are differences between the results. The experimental data in the study conducted by Manav [8], 4000 K – 500 lx, 4000 K – 750 lx, and 4000 K – 1000 lx were perceived as comfortable and spacious; these subjective evaluations are positive adjectives and they are short-term responses to the immediate environment. Though there are not identical subjective evaluations on the curve, these findings are tried to be matched to Kruithof's curve (1941); 4000 K – 500 lx combination is in the comfortable region, but 4000 K – 750 lx, and 4000 K – 1000 lx are on the line to the region of "colours appear dim or unnatural" region. Kruithof's curve (revised) support three of the lighting situations (4000 K – 500 lx, 4000 K – 750 lx, and 4000 K – 1000 lx) as being in the "pleasing" region.

Kruithof's curve is a tool for evaluating this relation, it gives a general idea. It is valuable as it suggests that there is a relation between colour temperature and illuminance for defining emotional space. Subjective judgments on the topic are not limited to being "pleasing" and "colours appear dim/cold" only as discussed in the works of Flynn et al [4–5], Hawkes et al [6], Manav et al [7–9], Knez [16], Veitch and Newsham [18]. Even today, new trends in lighting design lead us to discuss other issues such as tunable white light with LEDs, the light intensity on our eye and its effect on Circadian Stimulus, the influence of the light energy's wavelength on human bodily functions.

3. LIGHTING FOR TODAY

Today, regardless of the building typology, we always intend to achieve a well-designed, properly lighted interior space, which is "pleasing" and where we feel "comfortable". Though it is hard to have a consensus on subjective parameters such as visual clarity, relaxation, spaciousness, privacy (as they are related to subjective impressions), there are statistical methods to test and evaluate.

Starting from the beginning of the 21st century, in addition to the subjective impressions, novel issues such as light and health, human-centric lighting, circadian rhythm have become a topic of interest. A light beam not only passes through our eyes, which leads to seeing, but it also affects our hormonal activities and the rhythm of our body.

The well-known definition of circadian rhythm (to establish an internal replication of external day and night) and its influence on carrying an internal time information to all parts of the body, proves the fact of non-visual effects of light energy [12]. In case the immediate environment is dark, in the absence of light, the internal bodily signals continue to operate, but with a period more than 24 hours [13–15]. The external stimuli are necessary to activate the internal oscillator to 24-hour period. However, this might not be easy to satisfy quickly and immediately. A certain illuminance may not provide a signal to the internal oscillator to regulate the spectral sensitivity of the retinal photoreceptor. This fact may lead to the functioning of human metabolism inappropriately. Sleeping cycles, hormone activities, daily performance, immune system all are affected, which may lead to serious diseases. A lighting designer shall be a consultant to control these factors in order to satisfy a visually comfortable and healthy space.

Indoor lighting issues regarding visual comfort conditions are generally designed in reference to EN12464–1 [2], which refers to electric lighting systems. The Standard gives useful information in choosing and deciding on the size, as well as the location of the electric lighting systems. The required mean illuminance values on vertical and horizontal surfaces, Unified Glare Rating values can be calculated, luminaire position in accordance with working surfaces can be planned.

Research in the field suggests that lighting quality, which is described by colour property of light sources, human psychology, aesthetics, social and cultural factors, shall be considered in lighting design. However, lighting design is more than this, it has a power on human hormonal activities, personal wellbeing, immune system, performance as suggested by Bommel [3], Huiberts et al [12], Dai et al [13], Balia [14], Knez [16], Veitch [18].

In 2002, a novel photoreceptor in the retina of mammals was detected by David Berson, and we have learned that the effects of lighting quality is beyond visual effects. Light on the retina is the primary synchronizer of circadian rhythms. As we follow from recent research, there is a nerve connection between cones and rods in the eye and the visual cortex of the brain. The sensitivity between cone and rod systems varies with the wavelength of light, as well as colour of light. According to spectral eye sensitivity curves V', the human eye is not sensitive to extreme blue and extreme red. The eye has maximum sensitivity to green-yellow light. Research by scientists as Brainard [17] clarified that the sensitivity of the eye works differently than biological action curve. The sensitivity of the novel photoreceptor varies for different wavelengths (including light colour).

As the relation between the light spectrum and the human psychology is considered, it is seen that, though the visual sensitivity reaches its peak in the yellow-green wavelength region, the maximum biological sensitivity lies in the blue region. This difference shall be considered in lighting design because it is directly related to the non-visual effects of light.

A high-quality lighting installation goes beyond the visibility of the task and includes the visual appearance of the space [15–17]. Research on Unified Glare Rating (UGR) or Visual Comfort Probability (VCP) still continues. LED and/or other light sources with a higher colour temperature (stronger short wavelength content) cause more glare. Recent studies have shown that spectral glare sensitivity differs from spectral luminous efficiency function of the human visual system (with reference to the works of Fekete et al (2009) and Wördenweber et al (2007) as explained in CIE205:2013 [15] *Review of Lighting Quality Measures for Interior Lighting With LED Lighting Systems*. This fact leads to define the term Circadian Stimulus (CS), which is equivalent to percent melatonin suppression after 1-hour exposure to the light source.

In lighting design, it is important to consider illuminance according to the activity type, as well as the spectrum of light, exposure to a specific illuminant. In recent years, there is a consensus on evaluating the light incidence at the cornea. Two light sources may have similar colour temperature values, however, they might provide different Circadian Stimulus values. The difference is the result of spectral power distribution values. According to Figueiro [19] and her colleagues, it is accepted that light sources with higher colour temperature properties such as 5000–6500 K will generally provide greater Circadian Stimulus, however sometimes 3500 K sources have delivered less Circadian Stimulus than 3000 K sources.

Another important aspect in lighting design with respect to Circadian Stimulus is calculating the corneal illuminance (E_V) at the eye. Vertical illuminance is as important as the horizontal illuminance. Illuminance values are calculated in line with luminaires. This leads to select the most suitable luminaire type. It is advisable to use a direct-indirect luminaire system at the workplace [20]. Any lighting solution which can improve the visual ability with objective and subjective measures of alertness shall be developed and added to the surrounding. These designed items can be in the form of attached ones to the furniture (self-luminant office partitions) or self-standing ones such as light boxes, suspended ceiling with barrisol covering and automatic control system.

Another important item is related to lighting and ageing principles. It shall cover the visual needs of the user group. Eye detects and visual impairments shall be included in lighting design, as well as the circadian stimulus. Reports of Lighting Research Centre (LRC) on the topic highlights the power of illuminance, colour spectrum effect during daytime and night time as well. According to the findings of Figuera and colleagues [20], during daytime 400 lx / 6500 K combination or 550 lx / 2700 K at the eye for 2 hours is enough for Circadian Stimulus to reach 0.3–0.4, while during evening 50 lx / 2700 K combination at the eye for 2 hours is activating Circadian Stimulus to 0.1.

A series of experimental studies from 1970s until today and their scientifically sound findings highlighted the impact of the artificial lighting system on user performance and wellbeing [21–25]. However, the importance of daylight shall never be forgotten, it shall be adapted to the lighting system. The best of all is daylight, psychology, and physiology of lighting. Daylight spectrum and its effects on human being shall never be forgotten, always have to be added to the design.

4. DISCUSSION AND LIMITATIONS TO INVESTIGATE

CEN/TR16791 explains the spectral sensitivity of photoreceptors to assess lighting conditions with respect to their potential to achieve non-visual effects of light in humans [25]. Though it is difficult to measure non-image forming visual effects of light in humans, there are some recent findings. One of them is a research conducted by Koga Y. and Yamakawa M. [26], where the authors remark that vLEDs shall fit to mimic daylight; vLEDs are suitable for spaces and places, where colour aspects are a priority matter. Meanwhile, bLEDs render bluish colours despite the hue shifts. In addition, they suggest that bLEDs shall be selected when energy efficiency comes under photopic visual conditions. vLEDs have higher S/P ratios than bLEDs when the CCT is the same.

In line with the improvements in technology, new lighting solutions are reported. User-friendly lighting systems are adapted to architecture and interior architecture. Automatic controlled lighting systems, tunable lighting, user-centred design solutions are all technological improvements and design solutions which are frequently used.

In another study, energy performance (quantitative data) and visual comfort (qualitative data) of tubular LED lamps versus tubular fluorescent lamps are reported. Measuring and calculating illuminance, uniformity, power demand, total harmonic distortion, and power factor of tubular fluorescent and LED lamps allowed a comparison of the two lighting installations via quantitative methods. Qualitative data is evaluated by a visual task designed to evaluate the room impression and perception changes in the lighting systems. Results suggested that tubular LED lamps are similar to tubular fluorescent lamps in terms of lighting quality. The evaluated data on illuminance, glare, and visual appearance indicate that there is no difference in visual perception between lamp types. On the other hand, 22.8 % of energy-saving ratio could be achieved with the technology used in this field test; however, this ratio could be more than 60 % with inevitable development in LED technology [13]. The role of LEDs on Circadian Stimulus should be studied for similar settings and findings should be analysed from health-related issues.

CONCLUSION

The link between the stimuli (light energy) and the perception of space has been studied by many researchers. As the perception of the luminous environment depends on the adaptation of the visual system to the immediate environment, user differences, these factors shall be studied in lighting design issues. Simple perceptions (immediate responses) such as illuminance, luminance, and colour appearance show links to the luminous environment, whereas higher-order perceptions (spaciousness, complexity, visual clarity etc.) are more complex and need tenuous links.

While considering human responses to lighting conditions, it is recommended to satisfy:

- Not only horizontal illuminance (E_h) but also vertical illuminance (E_v), designing illuminance at vertical surfaces in addition to the horizontal surfaces shall be considered, light distribution in the space shall be designed and controlled;
- Luminance, as well as luminance contrast (in addition to general lighting, task lighting shall be satisfied), glossy reflections shall be controlled, shadows shall be considered, dark shadows which distract attention shall be avoided;
- Colour temperature of the light source (CT) is barely enough, spectral power distribution (SPD) shall be considered as well. Hence, colour properties of the surfaces shall be planned, colour contrast is important for visual acuity;
- Flicker (visual distraction and visual acuity).

The main concept should be to achieve a healthy environment, which addresses energy efficiency, cost, maintenance, and quality. User-friendly lighting systems should be adapted to architecture/interior architecture. User control over the lighting system is important for visual comfort, as well as circadian system. By dimming or increasing light output sets the inner atmosphere. Changing the colour of the light, as well as distribution, affects user mood, in other words, the space perception. Circadian stimulus effect should be considered at lighting settings as well.

The budget is another item to be considered in the process. Low-cost and quite effective solutions should be adopted to conditions. Integrating light colour to the colour scheme of interiors is another important design approach. For instance at offices, partition walls and/or work-stations can be self-luminous. Their colour can be designed. Red coloured partition may not suppress melatonin, hence 6500 K may suppress melatonin.

The importance of daylight shall never be neglected, it shall always be the first critical design task. However, in certain occasions, especially where no daylight is available, the question of "human factors, visual comfort, and lighting quality" always needed to be answered. Quality of lighting metrics shall be defined and included to the Lighting Standards such as *American National Standard Practice for Office Lighting* [21], *CIBSE, Code for Interior Lighting* [22], *CIE Standard, Lighting of Indoor Work Places* [23]. By taking the advances of the technological outcomes and systems, automatic control systems, human-centric lighting, tunable lighting, Circadian Stimulus effect shall be unified to lighting design. The lighting designer shall produce lighting solutions that provide sufficient luminance in the task area while enhancing the architectural/interior architectural features to provide some visually interesting parts.

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