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Emerging Concept of Human Centric Lighting in Literature Review

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***Abstract*— Human centric lighting is an umbrella concept which covers human health and well-being in general. As the conventional lighting techniques are based on horizontal workplane illuminance, it drives from the vertical eye level illuminance and its spectral distribution triggering the non-visual effects on humans. That is named as melanopic illuminance consequently. Its metrics have taken their place in lighting design literature and applications, with emergence of related standards subsequently. This literature overview contributes about the understanding the meaning human centric lighting due to transition from visual to non-visual effects of light, and how they direct recent research through light's impacts on human performance, emotions health and well-being, and relations to energy saving even. The shift from the concept of human centric lighting to circadian lighting design is obvious in very current studies.**

Keywords*— *human centric lighting, visual effects, non-visual effects, circadian lighting

I. Introduction

The idea of "human-centric lighting" was initially arose to carry the dynamic atmosphere of sunlight to people's living and working spaces and to prevent the deterioration of the biological clock and circadian rhythms. Human-centric lighting is the set of technical methods used to obtain the biological effects of daylight in an artificial lighting environment [1]. That is, lighting is designed to balance the human day/night rhythm. Its point of view has expanded to cover vision, comfort, psychology, human performance and well-being [2]. The aim is to obtain artificial light in natural light quality with human- centric lighting systems, and to ensure that human metabolism reacts in artificial lighting conditions as in day-lit environment. The question is what is the relationship between the human emotional state, performance, biological rhythm during the day and the light-dark rhythm of the world. The focus is to balance the visual, emotional and biological benefits of light for people. Daylight remains to be the reference for good light quality and is the basis for human- centric lighting [3,4,5].

Human-centric LED lighting systems offer dynamic lighting designs, modeling and predicting variations in parameters such as light intensity, illuminance and color temperature for different times of the day [6]. Human-centric lighting is associated with the non-visual effects of light on human metabolism and its effects on the circadian rhythm. Light affects people's attention, cognitive performances and emotional states [7]. As it is such a multidimensional terminology in the field of lighting, recent studies and knowledge has grown exponentially. As this concept has emerged in with recognizing the impacts of light spectrum on circadian rhythm [8,9], then continued with the proposals of the definitions of 'circadian light' and its measurements [10,11], followed by the calculations and models of parameter 'circadian stimulus' for the last 25 years [8,12]. Recently, it maintains its significance in the architectural lighting applications through a new conceptual shift and 'circadian lighting design' has settled its meaning in literature. This paper presents the concept of human centric lighting in terms of effects of light on humans, and how it is dealt with in current studies covering these impacts on vision, human performance, emotions, health and well-being in an emerging and growing trend due to daylight, dynamic LED lighting and circadian lighting design (Fig. 1).

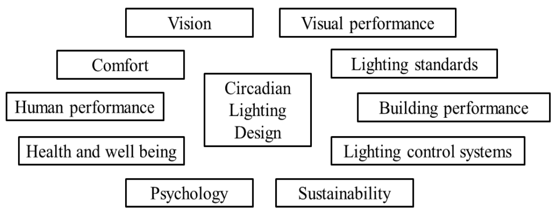

Fig. 1. Circadian lighting design.

The authors searched the databases such as Science Direct, Web of Science, Scopus and Google Scholar during this literature review, to find out the published studies earlier. The keywords are; circadian light, non-/visual/circadian effects of light, biological effects, alertness, cognitive performance, CCT and LED. To reach wider literature during the search process, more terms were included as circadian rhythm and human centric lighting. Although the earliest study was found in 1991, most recent studies from 2009 up to now have been examined (Table 1).

II. Effects of Lighting on Human Beings

Visual and non-visual effects of light occur through image forming and non-image forming photoreception [7,13]. By means of photoreceptors in the human retina, we can see our surrounding by image forming process while the non-image forming photoreception is responsible for the regulation of mood, physiology and behavior. This non-visual path affects individuals' biological clocks, their level of alertness and attention, and cognitive performance [14, 15,16]. The image and non-image forming routes in brain

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can determine human physiology and psychology. Visual effects such as vision, perception and information, and non-visual effects such as mental wellbeing, physiological arousal and performance became outcomes of seeing under lighting conditions [17,18]. (Fig.2).

A. Visual Effects of Light (Image forming path of the light)

Image-forming photoreception begins when light entering the eye activates rods and cones, which are light-sensitive cells in the outer layer of the retina that are primarily concerned with vision. So, we can visually perceive the forms and colors of objects around us, describe our position and direction, and interact with our environment [13, 15, 19]. The visual system allows to create a virtual model within the brain regarding the physical environment we are in. This model guides people in space, allows them to perform various visual tasks, but can be perceived differently by each person. [20].

Visual performance indicates the ability to perceive and process the visual environment accurately to perform visual tasks. It depends on lighting conditions as well as factors such as task characteristics, age. The thresholds for visual acuity, brightness, contrast, colors depend on lighting conditions and these factors play a significant role in the accurate and rapid perception of visual information [15, 19]. Accurate and fast detection of the relevant visual task components is essential for many daily tasks and underlines the relationship between visual performance and human functioning [21]. Lighting conditions enable vision, providing adequate light to perform visual tasks, --that is visual performance-- and affect visual comfort. [15, 19]. Visual experience is defined as how people experience and react to the visual environment. It is subjective and is possible owing to image-forming photoreception in the brain. The perceived objects through the light in the environment includes the individual's evaluations and expectations regarding the perceived object [22,23].

Lighting conditions experienced in offices have effects on the mood, motivation and satisfaction of the employees [22,23]. The actual affectional and cognitive functioning of employees may vary according to their beliefs and expectations. They refer to individuals' assumptions regarding the potential effects of light. If the lighting conditions of the environment do not match the expectations of the person, it can be evaluated as unsatisfying or inappropriate and may negatively affect the task performance. People prefer daylit work environments, as the movements and changes in light levels during the day are thought to be beneficial for mental wellbeing, performance and health [23, 24].

B. Biological Effects of Light (Non-Image Forming Path)

Recent studies discovered that the light coming to the retina is not processed only by rods and cones, but also by third photoreceptor named " intrinsically photosensitive Retinal Ganglion cell (ipRGc)" [26, 27]. They contain melanopsin, the most sensitive photopigment to short wavelength radiation. Short wavelength radiations induce the several of physiological responses related to neuroendocrine and eurobiological systems such as setting the main body clock, regulating hormones, maintaining alertness. The task of these receptors is to detect the non-visual information of light and transmit it to the Suprachiasmatic Nucleus (SCN) in the hypothalamus via the retinohypothalamic tract, to activate the circadian system. The information is also sent from the SCN to the pineal gland where it is used for hormone production and regulation of body temperature. This pathway of the light in the brain, which affects the mental and physical health, mood and performance of people, is called non-image forming photoreception [27, 28, 29].

Studies on the non-image forming photoreception have been mainly carried out in chronobiology and neuroscience laboratories, focusing on the behavioral and physiological effects of light entering the human eye, such as regulation of circadian rhythms, hormone secretion, core body temperature and brain activity. They showed significance of light exposure for attention and sleepiness of individuals in their task performance [30, 31, 32].

1) Circadian Effects of Light: Circadian rhythms refer to the approximately 24-hour cycles that can be found in human beings, plants, animals. It consists of regularly recurring biological incidences such as sleep and waking phases, feeding pattern, hormone production and brain activity [33, 34].

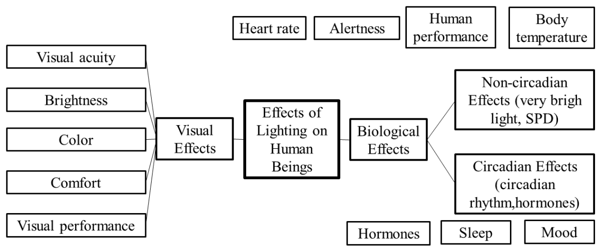

Fig. 2. Effects of lighting on human beings

Light is an essential component of circadian rhythm: it functions as a time cue by affecting the main clock, the SCN, and regulates the rhythms in different body components accordingly [30]. Metabolic activities such as hormone secretion (cortisol, serotonin, melatonin and adrenaline), regulation of body temperature and blood pressure in the human body occur in certain periods [7, 35, 36, 37]. The sleep hormone, melatonin works in the opposite direction of the cortisol cycle. In the morning, melatonin secretion decreases, cortisol production increases, and this cycle continues every 24 hours [31]. The human internal clock needs to be readjusted every day. When there is a phase shift between our biological clock and the daily light-dark cycle, human health is adversely affected in physiological and psychological aspects. A mismatch can occur between the internal rhythms of not only SCN but also different body components (such as lungs, heart, liver, muscles, etc.) and this is called internal desynchronization [37, 39]. This situation triggers several disorders such as daytime sleepiness, nighttime insomnia, irritability, mild depression, gastrointestinal distress, and so on. It also negatively affects cognitive abilities like memory deterioration, confusion, increasing error rate in workplaces [40]. People who work night shifts or travel over several time zones (jet lag) are typical examples of situations where the circadian rhythm is disrupted [35, 41]. These phase shifting effects of light depend on the duration and timing of light exposure, light wavelength and spectral distribution, light intensity [7, 35]. These insights are particularly relevant to the longer-term effects of light on the regulation of physiological and psychological processes (e.g. hormone production, sleeping pattern, vigilance, mood). However, light can also lead direct (acute) changes on human physiology, experiences and behavior.

2) Direct, Non-Circadian Effects of Light: Regardless of circadian rhythm, direct effects of light can occur at any time, day or night, by exposure to bright light [7]. Exposure to high light levels at night causes a sudden decrease in melatonin secretion and reduction of sleepiness. Nocturnal exposure to bright light can increase heart rate and core body temperature and regulate brain activity. Subjective alertness increased and attention and cognitive task performance improved [42].

Short-wavelength light instantly mitigates the negative effects of circadian impulses for sleep on alertness, performance. Subjects exposed to monochromatic blue light (460-nm light) at night for 6.5 hours had significantly lower subjective sleepiness rates, faster auditory reaction, and less failure due to inattention than those exposed to 555 nm light [43]. The lack of blue light as a result of wearing glasses that block wavelengths less than 530 nm does not suppress melatonin at night as with white light at the same illuminance (800 lx) [44]. The direct activating effects of nighttime light exposure were sensitive to short-wavelength light [45]. Exposure to light at 6500K resulted in greater melatonin suppression, along with improved subjective alertness, visual comfort and well-being in a study. Regarding cognitive performance, higher CCT levels led to significantly faster response times in tasks related to sustained attention [31]. Similarly, 2 hours of nocturnal exposure to self-luminous tablets viewed with the blue light can result in significant suppression of melatonin. Duration of blue light exposure is also important for human circadian rhythm [46]. The transition from low light intensity to high light intensity in the early morning suppressed melatonin secretion and caused a sudden increase in cortisol levels. [47]. Thus, many studies have shown that light can be used to reduce daytime and nighttime sleepiness, increase sustained attention and visual acuity by causing acute activating effects for the human body. These non-circadian, direct effects are most effective under high light levels and blue-spectrum light conditions.

III. Current Studies on Human Centric Lighting Design Concept

A. Regarding Daylight and Human Centric Lighting

The benefit of daylighting is not limited to energy consumption and providing comfort conditions, but it affects human health (psychology, eye health, hormone secretion, sleep/wake pattern, behaviors), work performance, students' learning ability, aesthetic judgements of building users and the perception of the physical environment [48, 49]. These effects occur when the visual, biological and mental benefits of light come together. These issues constitute the basis of the concept of human-centric lighting in particular; people feeling alert or non-stimulating; improving cognitive performances and emotional (mental) states; supporting the sleep and wake cycles is the content of this concept [50].

The spectrum of daylight was discussed in a research. Several types of glass types and surface colors were applied on a scale model, their effects on the interior physical environment were investigated by means of lighting simulations. Spectrum measurements of light in indoor and outdoor environment were taken, melanopic illumination was calculated. The potential of surface material colors to affect the circadian rhythm is higher than glass types [51]. The color of the window glass and occupants' switch on/off pattern for electric light and examined to see their effects on the daylight quality, attention/arousal. The blue glass decreased the level of attention/arousal of participants, but not modified the switch on/off pattern of artificial lighting significantly. Daylight passing through the bronze glass caused a general tendency to pleasantness and enhanced occupant's arousal/attention [52]. The window glass types, laminated, monolithic, coated and applied film glazing were the matter in another study. The spectral transmittance values of the glass affect the color rendering index values of the indoor daylight. As a result, some of the standard color rendering criteria were not met. The authors suggested conducting studies on the quality of daylight in actual physical environments, including users [53]. Light intensity and also the spectral power distribution (SPD) of daylight coming into the eye affect the circadian rhythm of the students and play a significant role in the arousal levels of the students [49]. A study examining light transmittance considered three types of glass: spectrally neutral, a brightness-reducing solextra and a brightness-enhancing solar bronze glass. The minimum acceptable light transmittance of window glasses became in the range of 25-38%. Window glass types should be studied in the context of the non-visual effects of light on humans [54].

Psychological and physiological factors have been associated with the working performance of VDT (visual display terminal) users in a study. To examine the cognitive work performance on the computer screen, the letter search test was performed, and the output was recorded in milliseconds. The next is the Stroop test, which is about determining the color of the word that appears on the screen. The attention/alertness of the participants was tested with the Karolinska Sleepiness Scale. When the shading on, that is, the illuminance was lower, their attention was higher in their color perception. Subjective performance differences were best observed in the morning hours. It has been proven that cognitive work performance increases when visual discomfort feelings are lower [55].

B. Regarding Color Temperature (CCT) of LEDs and Human Centric Lighting

Although the use of daylight is increased, artificial lighting systems are still needed. Lighting systems containing LED light sources are often preferred as they offer energy efficient and economical solutions. Despite the high amount of light emitted, the energy consumption values of these lamps are considerably low compared to fluorescents. Lamp life is quite long and maintenance costs are low [56]. Main concerns of subjective evaluations were cognitive performance, mood and alertness in work environments according to CCT and illuminance. Participants were less sleepy in bright light and the effect on long-term memory was mostly obtained in the cool light source [57]. Another article tested the effect of light color on the short-term memory and problem solving of high school students. Students performed better under warm white light. The blue light source impaired short- term memory and attention. In long-term memory, females performed better in artificial "daylight" white lighting than

TABLE I. SUMMARY OF CIRCADIAN STUDIES

Ref.	Year	Visual effects	Circadian Effects	Non circadian Effects	Daylight HCL	LEDs HCL	Circadian Lighting Design	Health-well being	Energy Saving
[54],[52],[53]	1995,2012,2017	✓		✓	✓				
[59] , [60]	2000, 2016	✓	✓	✓		✓			
[58], [62],[57]	2001, 2007,2017	✓	✓	✓		✓			
[48], [49]	2012, 2013			✓	✓			✓	
[56]	2015		✓	✓		✓		✓	
[61]	2018		✓	✓	✓	✓			
[63], [64]	2018, 2022	✓	✓				✓		
[51], [55]	2019	✓	✓	✓	✓				
[50]	2019		✓	✓	✓	✓		✓	
[65]	2020			✓	✓		✓		
[67], [70]	2020, 2022						✓	✓	✓
[69], [68],	2020, 2022	✓	✓				✓		✓
[66]	2022		✓	✓	✓		✓		
[71],[72],[73]	2022,2022,2023		✓	✓		✓	✓	✓	

males, while males performed best in "warm" and "cool" white lighting [58]. Positive effects were observed in both visual performance and cognitive and behavioral aspects of individuals with the enhancement of the lighting condition of the internal physical environment. Illuminance was an effective parameter [59]. The effect of color temperature on the performance and behavior of primary school students was the main target in another research. A classroom became the laboratory for physiological examinations and experiments under LED lighting conditions of three color temperatures (3500K, 5000K, 6500K). Authors suggested dynamic lighting systems according to color temperature groups; such as 3500K for easy, 5000K for standard, 6500K for intensive activities in learning environment [60]. A study applied a survey, tested cortisol levels of students in a classroom under fluorescent and LED lighting conditions. Stress hormone secretion was reduced under daylight exposure. Students needed to expose to daylight. In overcast sky conditions during winter, LED lighting is better to support the cortisol suppression of the students compared to the fluorescent system [61]. Low color temperature (CCT) values (2700 K - towards orange) provided relaxation, while higher CCT values (4000 K-towards blue) satisfied an impression of comfort and spaciousness for that space in another study [62].

C. Regarding Circadian Lighting Design

Very current research has been dealing with applications of human centric lighting. Circadian lighting design becomes the central concern. The impact of lighting design parameters on circadian effect, specifically, corneal illuminance, is the topic in a study [63]. It examines room average surface reflectance, window-to-wall-ratio, light distribution and geographic locations, and proposes certain equations to calculate circadian illuminance to be used in circadian lighting design. Another study analysed circadian stimulus, equivalent melanopic lux and circadian light. They suggested a new design to enhance insufficient circadian metrics for both daylight and artificial lighting conditions, modifying the ceiling surface colour and type of lamps [64]. Daylighting design can be evaluated or set up due to circadian ideas. To understand and test the non-visual effects of daylight, reliable and applicable methods are necessary as a study focused on this research problem [65]. Varying spectral irradiance reaching to a person's eye is modelled. So, dynamic character of daylight is evaluated to detect whether and how it changes humans' non-visual aspects according to orientation, obstructions and locations. Even a study about CBDD defines their approach and assessment as being "a complete lighting design" if human centric lighting techniques are applied. Authors of this research introduced human centric lighting into daylighting design and combined necessities of dynamic artificial light according to school children's activities and requirements of daylight metrics, sDA and ASE together [66]. Because of such interest and focus on implementations of circadian lighting design, some researchers interested on a research gap which inquires the relation between energy consumption and circadian lighting designs, meeting their requirements of building standards (WELL Q2 2019, UL Design Guideline 24480, and CHPS Core Criteria 3.0). There would be certain increase in energy consumptions while satisfying circadian lighting requirements, due to higher illuminance and occupation hours. Surface reflectance and view positions are the other factors affecting circadian metrics [67]. A similar lighting design including energy performance depicted that higher melanopic illuminance and colour temperatures to satisfy circadian standards in design can result in glare. [68]. A study tested how combinations of wall colours and glazing type affect circadian lighting metrics, CS, EML and photopic illuminance, under daylight. Materials with high transmissivity or reflectance can result in better circadian environment [69]. Researchers studied brightness for visual sensations in terms of melanopic illuminance, CCTs and SPDs by tuneable LED lighting. Energy saving suggestions are implemented in this circadian design [70].

D. Regarding Health and Well-being

Daylight supports psychology of humans [48, 49]. Emotional and mental states can change positively by daylight [50]. LED light is associated with some negative effects on human health. These effects include issues such as glare, optical damage, LED flicker, nocturnal exposure to LED light, toxic chemical content of LEDs in detail [56].

The circadian impact on health can be visible i.e. in sleep attitude. A study analysed the melatonin concentration under lighting scenarios and commented on participants sleep quality. Dynamic lighting provided positive impact on sleep quality, even gradually day-by-day. A backward lighting pattern was proposed significantly, including yellowish lighting at the first hour in the early morning after waking up, then a static lighting with 6000K CCT during the day, then medium white lighting in the evening and higher white lighting just before bedtime. The benefit of this lighting schedule is suggested for people who suffer from adaptations due to work-time-shifts and jet-lags [71]. Similar recent experimental studies found similar results, even when they examined cognitive performances and sleep quality together. Higher equivalent melanopic lux supports human health in the early morning while waking up. If humans are exposed to those illumination levels at wrong times, some health deficiencies may occur due to circadian system, as they depicted. Sleep has the vulnerability in that sense [72,73].

IV. Discussion and Conclusion

Recent 30 years witnessed the development of human centric lighting, including initial attempts related to visual and biological effects of LED lighting. Then, researchers realized similar effects of daylight and integrated systems. Following studies emerged health and well-being concerns together with new lighting standards. The conventional lighting design targets meeting required horizontal illuminance for visual performance and/or certain luminance ratios for brightness control for visual comfort. Though knowing the physiological and psychological impacts of light, recent researchers and lighting companies witnessed the development of knowledge about non-visual effects of light on humans and they contribute to the emergence of circadian lighting design. So, the standard approach to lighting design has turned to be human centered approach. We expect to see further growing research regarding the knowledge of circadian metrics and energy efficiency and sustainability lighting requirements in a holistic way.

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