LIGHT, HUMAN COGNITION AND LIGHTING DESIGN

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Abstract**—** This paper aims at looking at the effects of light on cognitive responses through elaborating the current knowledge on the ipRGC photoreceptor cells and how they influence the circadian rhythm as well as cognitive processes of the body throughout the day. Experimental studies in the literature are discussed and the lighting design approach corresponding to the non-visual effects of light on human cognition, the human centric lighting approach is explained.

Keywords**—** *Light, Vision, Lighting, ipRGC, circadian rhythm, Human centric lighting*

1. INTRODUCTION

Among the five senses the human body has been equipped with for sensory inputs, vision appears to be the most dominant when it comes to observing the world around us. Without light, the human eye can not perform the task of seeing. When light is present, the eye uses the photoreceptor cells in the retina, namely rod and cone cells, to transform the light energy into elecrical signals which the brain can process and form a visual understanding of the objects and the environment around us.

Until 2002, scientists thought that the process of seeing was only dependent upon the rod and cone types of photoreceptor cells. However, Berson and his colleagues brought another type of photoreceptor cell, namely the intrinsic photoreceptive retinal ganglion cell (ipRGC) into light through blocking the synaptic input from rod and cone cells in the rat retina and following the synapses from retinal ganglion cells when subjected to light [1]. These special cells detect the ambient luminous intensity as well as the spectrum of light and according to this detection process, regulate the release of melatonin from the pineal gland through which the circadian rhythm is adjusted. Thus, the eye is responsible for two different types of responses: visual and non-visual. The literature refers to this distinction as image-forming (IF) and non image-forming (NIF) processes as well [2]. There are numerous studies in the literature which show that lighting can manipulate the physiological arousal, neural activity, hormone production, and subjective alertness of human beings, along with cognitive processes such as attention, inhibitory control and working memory [3]. This paper aims at taking a look at the effects of light on human beings on these different levels and elaborate the recent lighting design approaches using these effects as their point of origin, such as human centric lighting design.

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2. LIGHT, VISUAL AND NON VISUAL RESPONSES

Among electromagnetic waves, light constitutes a small range falling between 380 nm and 800 nm. The previously mentioned cone and rod cells are responsible for photopic (daytime) vision corresponding to luminance values approximately above 10 cd/m^2 and scotopic (night time) vision corresponding to luminances approximately below 0.001 cd/m^2, respectively. In between these two luminance values, mesopic vision, in which both cone and rod cells are active, takes place. In order to quantifty the radiation affecting human visual response, the The Commission Internationale de l'Eclairage (CIE) luminous efficiency functions are utilized. The CIE has defined two luminous efficiency functions quantifying human visual response according to wavelength, V(λ) for photopic vision and V'(λ) for scotopic vision. Fig. 1 shows the CIE Standard 2° Photopic and Scotopic Luminous Efficiency Functions of Wavelength plotted using the values given in the IES Lighting Handbook [4].

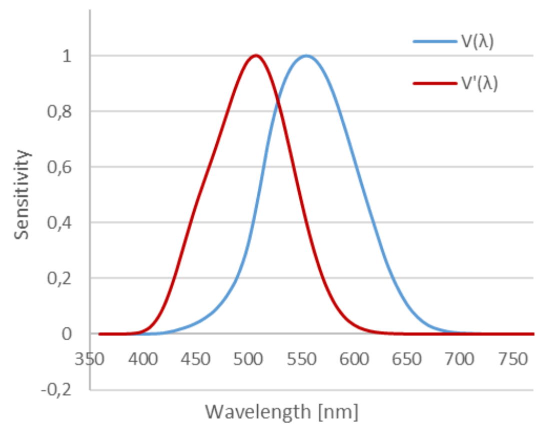

Fig.1. CIE Standard 2° Photopic and Scotopic Luminous Efficiency Functions

The CIE photosensitivity curve shows that for daytime vision, the maximum sensitivity of the human eye is at 555 nm, corresponding to green light on the electromagnetic spectrum. This peak sensitivity, however, changes for non-visual responses; research made on humans, macaque monkeys and rodents show that the most effective wavelength range is between 459 and 485 nm, corresponding to blue light instead of green. There are also studies showing that the change of color from green to blue affects the aforementioned physiological attributes, such as melatonin rhythm and secretion, body temperature, heart rate elevation, sleepiness reduction and improvement of alertness.

The non-visual responses to light are strongly related to the photopigment melanopsin, expressed by ipRGCs, whose

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maximum sensitivity is approximately at 480 nm. ipRGCs prevail throughout the retina in low densities and currently appear to be the sole connection of light and non-visual responses, however they receive time-varying information from rod and cone cells throughout the day as well [5].

2.1 The Circadian Rythm

The Circadian rhythm is a result of the earth rotating around its axis and exposing all living creatures to daylight and darkness in a 24-hour period. The name comes from the Latin words circa which means about and dies which means day. Throughout the day, the body temperature, hormone secretions, sleep orders, cognitive performance and numerous physiological attributes are affected by this process. The Suprachiasmatic Nucleus (SCN) situated in the mammal brain is responsible for controlling the circadian rhythm. In order to keep the SCN up to the 24-hour period, sensory inputs, mainly light is necessary, The literature refers to this phenomenon as “photoentrainment” [6, 7]. Thus light acts as an entrainment tool for the body to set its biological clock to the Earth’s clock [2, 8]. Human experiences such as jet lag, where traveling to different time zones affect the sleeping behaviors are results of the shift in the circadian rhythm. In such a case, sleep deprivation results in fatigue and bad moods as well, thus these types of examples show that in addition to human behavior, human emotional state is also influenced by the circadian rhythm.

2.2 Cognitive Effects – Experimental Studies in the Literature

Visual tasks are formed of visual, cognitive and motor mechanisms [9]. The literature shows that the concepts explained in this paper so far have a strong influence on non-visual functions such as the amelioration of alertness and performance on a number of cognitive tasks and that brain function and cognition are directly manipulated through lighting and its properties. According to several studies, light exposure can affect hormone secretion, heart rate, sleep propensity, alertness, body temperature, retinal neurophysiology, pupillary constriction and gene expression [7, 8, 10-13]. Cognitive processes such as attention, executive functions and memory are strongly affected by the circadian rhythm in human beings. There exists a strong fall in cognitive performance at night time with a strong rise at day time. There is also research showing that light can directly affect cognitive performance through exposure both at night and day for actions such as visual search, digit recall, serial addition-subtraction, two-column addition, logical reasoning task, letter cancellation task and simple reaction time tasks [5]. For instance, 94 white collar office workers who were exposed to blue-enriched white light for four weeks during daytime showed improvements in terms of subjective alertness, performance and decreased evening fatigue as well as night-time sleep quality [13]. A similar study by Milles et al. showed that high values of correlated color temperature (CCT) could improve the wellbeing and productivity of occupants in a corporate environment [14]. Both studies used 17000 K CCT light sources and on the lighting design point of view, the visual comfort created through such high levels of CCT is a question mark. However, the study by Chellappa et al. in which a comparison of warm CCTs to 6500 K showed that the latter cold light color created a greater melatonin supression and ameliorated subjective alertness, well-being and visual comfort [15].

In other studies, neuroimaging, namely Positron Emission Tomography (PET) and functional Magnetic Resonance Imaging (fMRI) techniques were used to investigate the influence of light exposure during daytime on attributes such as auditory perception, attention, executive function, working memory and updating [16-18]. An important finding was that these techniques were able to detect the effect of light on active cognitive brain activity. Another finding was that light triggered many different subcortical and cortical regions in the brain, responsible for different cognitive attributes. Using different wavelength, thus different colored light in the experimental studies, it was also seen that blue light of wavelength approximately 460 nm provided better performance results compared to green light of wavelength approximately 550 nm when a simple vigilance reaction time task was carried out. In a more complex task, the fMRI results showed that blue light (appr. 480 nm) ameliorated brain responses compared to green (appr. 550 nm) and violet (appr. 430 nm). The amount of light, which is related to the duration of exposure and also luminous intensity was among the findings which were found to be related to the time course as well as which region of the brain was affected. The studies clearly show that light exposure, depending on its duration and amount of photons as well as its wavelength has strong influences on cognitive brain responses [5].

3. LIGHTING DESIGN APPLICATIONS

While the visual and non-visual effects of light on human beings is a subject that continuously evolves as scientists receive more findings from their studies on the human body, what delivers light to humans is lighting. Therefore, the correct design of lighting is of upmost importance for human beings to benefit from the properties of light elaborated in this paper. A novel approach originating from these ideas is Human Centric Lighting followed by a much larger concept, People Centric Buildings.

3.1. Human Centric Lighting

Houser defines Human Centric Lighting as “Evidence-based lighting solutions optimized for vision, performance, concentration, alertness, mood, and general human health and well-being. HCL balances visual, emotional, and biological benefits of lighting for humans, recognizing the role of light on human vision, psychology, and physiology” [19]. Boyce comes up with a similar explanation of this relatively recent term, emphasizing the visual and non-visual effects of light in the definition he makes for his editorial piece Exploring Human Centric Lighting [20].

Human Centric Lighting has become a popular topic with the advancement of light emitting diode (LED) light sources, which make it possible to easily manipulate the wavelength of the light delivered through the monochromatic character of these novel light sources. Using this property of LEDs, which was not possible before with conventional light sources, it is now possible to change the color of light, or in other words the wavelength content of the light, throughout the day to the benefit of the user. This makes it possible for the lighting design to mimic daylight or to omit the undesired wavelengths at certain times of the day to increase the motivation, alertness and mood of users; put in another way, to manipulate cognition along with visual comfort. Thus both aspects discussed in this paper, the visual and non-visual attributes of light are utilized in human centric lighting.

3.2. People-Centric Buildings

The concept of People-Centric buildings takes the Human Centric Lighting understanding several steps further by adding other building components into the equation, temperature, air and noise for the health, well-being and productivity of building occupants. A non-profit platform funded by the European Climate Foundation, Buildings 2030 has recently published a white paper on the subject "Building 4 People: People-Centric buildings for European Citizens in order to motivate European Union member states to meet the Conference of Parties - COP21 Paris Agreement goals and European Union's 2030 climate and energy targets [21]. The white paper emphasizes the importance of lighting in terms of people-centric buildings and gives examples of applicTations made in school, office and hospital buildings, increasing the productivity, learning progress and cognitive functioning of the occupants of these different buildings.

4. CONCLUSIONS

Seeing may very well be the most important sensory input human beings receive. With scientific advancements, it became apparent that the human eye was not made only for vision and that light brought non-visual effects on the human body as well. Current research shows that there is still a lot that we don't know about the complex relationship of light and the human cognitive system, but experimental studies provide promising results for improving the cognitive performance of human beings, their well-being, physiological conditions as well as mental health, a concept that has not been discussed in this paper, through manipulating lighting conditions. The fact that the discovery of the ipRGC photoreceptor cells coincided with the recent technological developments in the field of lighting, in other words LEDs becoming general lighting sources brought up the possibility of new lighting approaches. Human Centric Lighting, which previously translated into using higher CCT light sources can now be applied in its actual means if the lighting design is deeply elaborated according to the scientific findings in the literature.

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BIOGRAPHY

Lale Erdem Atılgan obtained her BSc, MSc and PhD degrees from the Electrical Engineering Department of Istanbul Technical University in 2004, 2007 and 2014 respectively. During her PhD studies, she received the Jean Monnet European Union Scholarship and spent over a year at the Light Technology Institute of Karlsruhe Institute of Technology, Karlsruhe, Germany, doing research on lighting technologies, specifically Light Emitting Diodes (LEDs). She's a member of the International Commission on Lighting as well as the Turkish National Committee on Illumination. Her research areas are lighting technologies, LEDs, LED driver systems and energy efficiency. She's currently a member of the academic staff of the Electrical Engineering Department of Istanbul Technical University.