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The open issue of color management in circadian interior design between the practice of lighting and color design

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Abstract

In the last 20 years, research has been developed in the field of chronobiology and physiology to demonstrate the relationship between the health of the human organism and the light radiation that enters our eyes. These are known as the Non-Image Forming (NIF) effects of light. Nowadays, it has been scientifically shown that light radiation's parameters that affect our physiology are the quantity, the spectrum, and the time of exposure. These fundamental parameters impact our living in interiors, illuminated by artificial light, with scarce or no natural lighting. Until a few years ago, in the design field, there was a lot of skepticism about these aspects that the 2017 Nobel Prizes in Medicine genetically demonstrated. Today there is a growing interest developed in the lighting design sector, which, however, sees the need to deal with a holistic interior design vision. In this article, a review of current knowledge is proposed to favor the relationship between lighting and color design.

Keywords: interior design, lighting, color, circadian.

Introduction

In the last 200 years, human life has transformed with mass migration from the countryside to urban centers and the industrial revolution. In a few generations, we moved from a working life conducted outdoors, in the country, to one mainly indoors, with a limited supply of natural light and exposed instead to artificial light. We should remember that in Europe, in 1800, only 2% of the population lived in cities. In the early 1900s, this had risen to 15%. In the 21st century, most of the European population lives in cities (UNICEF, 2008) and works in closed spaces; most of those living outside urban centers do not work outdoors. It is estimated that in today's industrialized societies, we spend between 80% and 90% of our time indoors (Evans, 2003; Boubekri, 2008). Indeed, our body is made to function and synchronize itself according to the rhythm of the continuous variations of natural light. Our physiology would require exposure to natural light during the day and complete darkness at night to promote sleep, with its regenerative cycles fundamental for health, happiness, and wellness (CIE, 2001).

In the interiors, the light and colors of the perceived image are entirely different from the open-air ones, in which we have evolved for millions of years. The change in the environments in which we live and our exposure to artificial lighting are both factors that have been introduced very recently (Stevens, 1987). With the 2017 Nobel Prize in Medicine (Young, 2017) awarded to Hall, Rosbash, and Young, the issue of circadian effects on people's well-being in interiors has been brought to the attention of industry manufacturers and innovation-minded designers (Figueiro, Nagare and Price, 2018).

The circadian system

The word "circadian", composed of the Latin words circa and diem, describes a periodic biological cycle that lasts roughly one day (Halberg et al., 2003). In the human organism, there is a timed system that lasts about 24 hours, managed by the suprachiasmatic nucleus in the innermost and primitive part of the brain, through which all the physiological processes, such as sleep and cell regeneration, hormone production, blood pressure, body temperature, nutrition and digestion, alertness, coordination, and muscle strength, are managed (Klein, Moore and Reppert, 1991). The

human body is made to function and synchronize according to the rhythm of the continuous variations of natural light (Czeisler et al., 1981). Our physiology requires us to be exposed to natural light during the day and complete darkness at night, promote sleep, a fundamental function for health, and ensure the proper phasing of our circadian rhythm (Wright et al., 2013). Some lighting designers try to mimic the behavior of natural lighting with indoor artificial lighting.

Many situations can disrupt our circadian rhythm. A known factor is, for example, flights between multiple time zones. Jet lag occurs due to the phase shift between the sleep cycle, internal organs, and the new circadian rhythm induced on the body by the different timing of the received lighting (Boulos et al., 1995). The social context, such as night shift work (Eastman et al., 1995), can also lead people to excessive evening light exposure, consciously or otherwise, contributing to a delayed phase shift in the circadian rhythm, defined as social jet lag (Joo et al., 2017).

Sleep disorders could be caused by circadian rhythm disruption and are often underestimated by general medicine (Institute of Medicine (US) Committee on Sleep Medicine and Research, 2006). Disruption of the circadian rhythm can occur in delay, DSPD (delayed sleep phase disorder), or in advance, ASPD (advanced sleep phase disorder) (Phillips, 2009). These phase shifts could become pathological. Research has shown that circadian cycle disruption can cause migraines (van Oosterhout et al., 2018), headaches (Pringsheim, 2002), irritability (Evans and Davidson, 2013), night (Bach et al., 2019) and daytime (Jokubauskas et al., 2019) bruxism, seasonal depression (Rosenthal, 2006), immune system deficiencies (Christoffersson et al., 2014), chronic fatigue (Bonsall and Harrington, 2013), obesity (Reiter et al., 2012) and diabetes mellitus (Cedernaes, Schiöth and Benedict, 2015). There is also discussion of an increased likelihood of developing certain types of tumors due to the weakening of the immune system (Stevens et al., 1992; Schernhammer et al., 2003, 2013).

Artificial Circadian Lighting

Why not use artificial lighting indoors to phase our circadian rhythm correctly? While the idea may seem valid and healthy, the design approach is often weak (Figueiro, Gonzales and Pedler, 2016). Being this an ongoing field of research. Some methods of light evaluation have been included in specific national standards without design guidelines (IES, 2018; DIN, 2021). Although there are no reference standards in this field, some basic design guidelines can be drawn to improve our life indoors. We can define some features that the lighting system should have to be considered circadian:

- Indoor artificial lighting in interiors should be dynamic, with quantity and CCT varying throughout the day, similar to natural light variations.
- In the phases of relaxation and evening, it is advisable to use a warm CCT with low lighting levels to avoid disrupting our circadian cycle.
- To promote the proper phasing of the circadian rhythm, lighting in the first half of the morning and the first half of the afternoon should be higher and have a cooler CCT.
- Today, in the absence of specific standards, to determine if the light reaching the eyes has circadian effects, the reference model proposed by (Rea, Nagare and Figueiro, 2021) can be used and calculated using software tools available online (LRC, 2018; OSRAM SYLVANIA, 2018).
- Light sources with high color rendering should always be preferred. The actual color rendering should be evaluated using the TM-30-20 standard.

Anyway, a lighting product or lighting design is not enough to stimulate the circadian system properly. It is the design of the environment as a whole that must be circadian because we always instinctively avoid looking directly at light sources because of glare. Instead, we are constantly observing the surfaces of the environment around us with their colors.

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The "surface color" factor

We must remember that, from the design point of view, the light that reaches the users' eyes must be evaluated because it is the only aspect that affects the circadian system. So, the spaces, expected human positions, and activities must be analyzed in detail. The light that our eyes receive, and which contributes to the visual system as well as the circadian system, is almost always diffused light from the surfaces of the environment, which in turn have physical characteristics that reflect to our eyes light generally modified by the light spectrum coming out of the luminaires. The main studies (Brainard *et al.*, 2001; Thapan, Arendt and Skene, 2001) on the response curves of the circadian system were done in a laboratory, with dilated pupils and a fixed gaze inside a Ganzfeld sphere, with nearly monochromatic lights projected. These experiments lack any contribution from spectral reflectance of our everyday life and how they really reflect light to our eyes.

Within this context, the NIF effects on people's mood and pleasantness (Veitch and Newsham, 1998; Borisuit *et al.*, 2015) attributed to CCT will also come into play. Anyway (Boyce and Cuttle, 1990) more correctly observed that the evaluation of the interior space does not depend only on the CCT of the light but also on the other natural and colored elements that may be present. The aspect lacking in evaluating circadian effects is the color in the surfaces of interiors and furniture, that is, what human eyes watch in that 80-90% of the time they spend indoors.

For the design application, a correct evaluation of circadian effects implies considering the colors of the interiors and the way they modify the perceived light (Bellia, Pedace and Fragliasso, 2017). Some studies have been done using color samples or computer images which are difficult to transfer to the design field (Anter and Billger, 2010), while other studies have been done in the field (Kwallek *et al.*, 1996; Küller *et al.*, 2006; Hårleman, Werner and Billger, 2007; AL-Ayash *et al.*, 2015; López-Tarruella *et al.*, 2019) with variations that may also be of cultural origin (Hogg *et al.*, 1979; Ou *et al.*, 2018)

Conclusions

From the point of view of interior architectural design, there is a total absence of tools that allow us to design light and color together. Tools would be needed to calculate and quantify the interaction between lighting and surface colors to evaluate the light's characteristics that reach users' eyes from a quantitative and spectral point of view. These new tools should hopefully be developed within the Building Information Modeling methodology to enable the integrated design of light and color. However, today only the photometric data of the light sources are starting to be available in BIM; the spectral data (Rossi, 2022) and those concerning the spectral reflectance of the authentic materials used in Interior Design are still missing (Guarini and Rossi, 2021)

This paper presents a short review for bridging the gap between lighting and color design, trying to enter partly into the field of a new interior circadian design to simulate natural lighting and the environment best. There is, therefore, a need to carry out more research in the field to be able to assess human beings in real-life settings, also considering the time factor (Figueiro, 2013), with the dynamic and chromatic variability that LEDs can have today (Wang *et al.*, 2014).

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