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A novel circadian daylight metric for building design and evaluation

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ABSTRACT

This paper extends the applicability of emerging frameworks for evaluating the non-visual effects of light through the development of a novel area-based daylighting metric addressing goals of human circadian stimulus and entrainment in buildings. Procedures using annual, climate-based daylight modeling of eye-level light exposures are developed to analyze and map indoor environments in regard to spatial and seasonal changes in the availability of a circadian-effective daylight stimulus. Because the biological effects of light exposure are not instantaneous, a novel approach is developed to assess the duration of an effective stimulus on a daily basis, as well as the frequency an effective stimulus is present over the course of a year. Results can be used to identify and visually examine building zones where long-term occupancy may lead to disruption of the circadian system in the absence of supplemental electrical lighting capable of effective circadian stimulus. The metric and visualization techniques are implemented in a parametric, simulation-based workflow utilizing publicly available software tools. The workflow can be used to assess and differentiate the performance of various daylighting strategies during the design phases of a project, or to examine existing spaces. The applicability of the workflow is demonstrated using two example models: a portable school classroom, and a generic open-plan commercial office floor plate.

1. Introduction

Standards and practices for lighting design were developed to serve human visual needs prior to scientific understanding of the important role light plays in maintaining healthy human biological functions. The discovery of a third class of photoreceptors in the human retina [1–4], referred to as Intrinsically Photoreceptive Retinal Ganglion Cells (ipRGCs), has led to a growing interest in the non-visual effects of light on human health and well-being. In contrast to rod and cone photoreceptors, which serve as inputs for low-light and color vision, the ipRGCs serve no visual (image-forming) function. Instead, ipRGCs play a critical role in synchronizing human *circadian rhythms* to the 24-h light/dark cycle of the local environment. Notably, the action spectrum of light for the circadian system is shifted towards shorter wavelength (~490 nm) "blue" light relative to the visual system, which is maximally sensitive to (~555 nm) "green" light [5,6]. As a result, humans are not well equipped to self-report the presence or intensity of circadian-effective light based on visual perception.

Inside buildings, where adults spend 87% of their lives on average [7], lighting is often provided by electrical sources that are adequate for performance of visual tasks (i.e. stimulation of the visual system), but can lack the appropriate spectral composition and intensity required to stimulate the circadian system. All zones within a building that do not regularly achieve the lighting conditions necessary for effective circadian stimulus can be labeled as *biologically dark*, and considered as zones where sustained occupancy over extended time periods (e.g. regular workday schedules) may present a risk for disruption of the circadian system in the absence of supplemental electrical lighting capable of effective circadian stimulus.

As evidence of the health impacts of light exposure grows, it is import for designers to have metrics and guidance to evaluate project performance in regard to the non-visual effects of light alongside more commonly used lighting metrics related to visual task performance (e.g. horizontal workplane illuminance and illuminance uniformity), visual discomfort (e.g. probability of glare), lighting energy savings (e.g. electrical lighting energy reduction from photocontrols), and Indoor Environmental Quality (IEQ) (e.g. compliance with the U.S. Green Building Council's LEED Daylighting Environmental Quality (EQ) credit) [8].

There are currently no minimum requirements for daylight access in buildings to support circadian entrainment. However, the

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International WELL Building Institute has recently developed a building certification system with the stated objective of, “measuring, certifying and monitoring the performance of building features that impact health and well-being” [9]. One of the preconditions for certification, (entitled “Circadian Lighting Design”), is the provision of sufficient melanopic light intensity for work areas. The term “melanopic” refers to a new photometric measure of light intensity weighed by the sensitivity of the melanopsin-containing ipRGCs, and is discussed further in Section 2.1. While the precondition does not require the use of daylight to meet the requirement, the contribution of daylight can be included in simulation-based predictions (the specific compliance criteria and their current ambiguities are discussed in greater detail in the following sections). Despite the fact that compliance can be achieved exclusively through the use of electrical lighting, it is anticipated that designers will seek to meet such requirements to the extent possible through the use of daylight, and supplement insufficiently-daylit zones with appropriate electrical lighting.

The emergence of requirements for circadian lighting design signals a growing interest in the challenge of translating scientific knowledge into actionable information that can be applied to improve the well-being of building occupants. It should be emphasized that the development of a circadian daylight metric relies on a combination of available scientific information and expert judgments related to the timing, intensity, duration, wavelength and past history of light exposures. A rationale for how each of these factors is addressed is included in this paper along with discussion of additional factors that are not directly related to building design, such as age and work schedule requirements. The reader should expect the judgments made in this paper to be revisited as scientific understanding of the human non-visual response to light evolves. Nevertheless, it is important for designers to have access to design support tools and performance criteria developed on available knowledge to specifically address non-visual effects of light during design. Such tools can help designers to better assess, understand and improve the circadian effectiveness of various daylighting strategies.

This paper extends the applicability of emerging frameworks for evaluating the non-visual effects of light through the development of a novel area-based daylighting metric addressing goals of human circadian stimulus and entrainment in buildings. Procedures using annual, climate-based daylight modeling of eye-level light exposures are developed to analyze and map a space in terms of the frequency of a circadian-effective daylight stimulus. Because the biological effects of light exposure are not instantaneous, a novel approach is developed to assess the duration of an effective stimulus on a daily basis, as well as the frequency an effective stimulus is present over the course of a year. Results can be used to identify, quantify and visually examine building zones where long-term occupancy may lead to disruption of the circadian system in the absence of supplemental electrical lighting capable of effective circadian stimulus. The metric and visualization techniques are implemented in a parametric, simulation-based workflow utilizing publicly available software tools. The workflow can be used to assess and differentiate the performance of various daylighting strategies during the design phases of a project, or to examine existing spaces. The workflow files are available for download here [10]. The applicability of the workflow is demonstrated using two example models: a portable school classroom, and a generic open-plan commercial office floor plate.

2. Previous work

There are a number of parameters known to control the circadian system's response to light that are directly impacted by building design. These include the timing, intensity, duration, wavelength and past history of light exposures [11]. The following sections describe the rationale and assumptions made in regard to each of these parameters to develop a procedure to analyze and map a space in terms of the frequency of a circadian-effective daylight stimulus.

2.1. Spectrum and intensity of light exposure

To study the potential circadian effects of various light sources it is first necessary to quantify light exposure in biologically meaningful units. Fig. 1 shows the spectral efficiency function of the melanopsin-containing ipRGCs (black curve) developed by Enezi et al. and Lucas et al. [12,13], referred to as the melanopic spectral efficiency function (annotated here as C-lambda). The melanopic spectral efficiency function can be used to calculate melanopic illuminance (reported in units of Equivalent Melanopic Lux (EML)) for various light source Spectral Power Distributions (SPD) [14]. Fig. 1 also shows the spectral efficacy function of the visual (photopic) system (V-lambda) along with the SPDs of three Commission Internationale de l'Eclairage [15 CIE] daylight illuminants, (D55) sunlight, (D65) overcast sky, and (D75) north sky daylight. Fig. 1 shows that the maximum efficacy of the circadian system (C-lambda) is more closely aligned with the maximum power of the three daylight SPDs compared with the photopic function (V-lambda). In contrast, Fig. 2 compares the spectral response of the visual system (V-lambda) and the circadian system (C-lambda) to the spectral power distribution of a “standard” fluorescent lamp, (CIE illuminant F11), which represents a narrow tri-band fluorescent of 4000° Kelvin color temperature. Fig. 2 shows that the peak power of two of the three most prominent wavelength bands fall largely outside sensitivity of the circadian system (C-lambda). The introduction of EML as a unit enables designers to differentiate the relative “circadian efficacy” of various light sources (such as daylight vs. fluorescent) that may produce the same visual effect.

Several researchers have proposed models of the spectral sensitivity of the circadian system that can be used to relate the SPD from various light sources to objective and subjective stimulus effects. The model developed by Rea et al. [16] is based on published studies of nocturnal melatonin suppression using lights of various SPDs. The model relates a given SPD to a Circadian Stimulus (CS) effect from 0% (no effect) to 70% (maximum suppression level achievable after 1-h) characterizing the relative effectiveness of the source as a stimulus. The model can be applied to convert various light sources to units of Circadian Lux (CL_A) for relative comparison using a publically available circadian stimulus calculator [17]. The model developed by Andersen et al. [18] is based on both nighttime [19] and daytime [20] studies and “sets a tentative lower and upper bound for the likelihood that a given light exposure will have an effect on alertness,” with a liner ramp-function applied to interpret intermediate values. The upper and lower bounds of the model can be converted into the standard photometric unit of illuminance (lux) using the approach described in Pechacek et al. [21] for any SPD of interest by applying a conversion factor. For example, for D65, the lower bound is 190 lux, and the upper bound is 870 lux. Finally, Amundadottir et al. [22] have developed a framework to describe the circadian effectiveness of light that can be explored using an online calculation and visualization tool [23]. The framework incorporates dose-response models of melatonin suppression, melatonin phase shift, and perceived alerting effect, enabling users to predict and compare the biological effect for various light source SPDs. The framework incorporates a lens transmittance model [24] and requires the user to specify the age of the observer to account for the relative loss in retinal exposure due to age. In specifying any threshold level, the age of the occupants is an

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