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The impact of room surface reflectance on corneal illuminance and rule-of-thumb equations for circadian lighting design

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ABSTRACT

Recently, corneal illuminance attracts much attention because it is closely related to important functions of indoor lighting. Especially, applying circadian light in the built environment places a challenging requirement on indirect corneal illuminance. In this work, rule-of-thumb equations are proposed to guide circadian lighting design: (i) for artificial lighting, $E_{\mathrm{cor,avg\ (i)}} = (\Phi/C_1)\cdot\rho/(1-\rho')$, where $E_{\mathrm{cor,avg\ (i)}}$ is the average indirect corneal illuminance at standing or sitting positions, Φ is the initial flux from luminaires, C_1 is a constant comparable to the total room surface area, ρ is the reflectance of the surface where the first reflection occurs, and ρ′ is the area-weighted average of surface reflectance; and (ii) for daylighting, $E_{\mathrm{cor,avg\ (i)}} = C_2\cdot \mathrm{WWR}\cdot\rho/(1-\rho')$, where C_2 is a constant, and WWR represents the window-to-wall ratio.

The equations above are validated by comparing against numerical simulation data obtained with the Radiance software. For artificial lighting simulation, various combinations of room surface reflectance, initial light distribution, and WWR are investigated; and for daylighting simulation, different combinations of surface reflectance, WWR, and geographic location are analyzed. The good fits to simulation data indicate that the proposed simple equations can provide reasonably accurate results for quick feedback at the field. It is also demonstrated that room surface reflectance has a dominant impact on indirect corneal illuminance. The approach of improving surface reflectance is more favorable than increasing luminaire flux or expanding window area, and therefore should be the recommended approach to achieve quality and efficient circadian lighting.

1. Introduction

Due to the direct relationship between visual task characteristics and illuminance on the task, traditional indoor lighting design practices focus on the illuminance arriving at horizontal working planes [1,2]. Recently, the importance of corneal illuminance continuous to rise. This is because corneal illuminance, or vertical illuminance at eye height in most cases, is particularly useful when evaluating important aspects of lighting functions such as lit appearance, visual communication, and non-visual circadian effect [1–8]. For example, cylindrical illuminance (mean value of vertical illuminance on a cylinder) is started to be recommended in codes and standards: according to the current edition of EN 12464-1:2011 [3], the mean cylindrical illuminance should be no less than 150 lx for places where visual communication is important (e.g., offices, meeting rooms and classrooms). Furthermore, the discovery of the non-image-forming intrinsically photosensitive retinal ganglion cells (ipRGCs) [9] and the ongoing research on non-visual effect of light reveal that an even higher level of corneal illuminance might be desirable in buildings where people stay for a long time during the day [4,10–14]. It is now well accepted that light plays a central role in maintaining a healthy circadian rhythm, and the amount of light received at eyes is one of the key factors [4–9]. Sufficient "light dose" during the day together with low light stimulus during the evening can promote synchronization of human body's "biological clock" with the local time on Earth [4,5,7,11,15–17], while insufficient day-time light exposure or inappropriate light at night (LAN) could cause circadian disruption [16,18] which, if lasts for a long time, could lead to a wide variety of maladies such as sleep disorders, diabetes, breast cancer, and cardiovascular disease [16,18–21]. Although the exact amount of corneal illuminance needed is still under debate, one thing clear is that currently, "the daily light dose received by people in western (industrialized) countries might be too low" (according to the CIE

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Nomenclature

A	The total room surface area
ab	The "ambient bounce" setting in the Radiance software
$A_{ceiling}$	The surface area of ceiling [m^2]
A_{floor}	The surface area of floor [m^2]
A_{wall}	The surface area of wall [m^2]
A_{window}	The surface area of window [m^2]
C_1	A constant comparable to the total room surface area
C_2	A constant determined by factors such as sky condition, window direction, and total room surface area
CCT	Correlated color temperature [K]
CL_A	Circadian light
CRI	Color rendering index
CS	Circadian stimulus
d	Index of agreement
E_{cor}	Corneal illuminance at a measurement point (mean value of eight eye-sight directions) [lx]
$E_{cor\ (d)}$	The direct portion of E_{cor} [lx]
$E_{cor\ (i)}$	The indirect portion of E_{cor} [lx]
$E_{cor,avg}$	The average E_{cor} value of all the measurement points within the active area [lx]
$E_{cor,avg(d)}$	The direct portion of $E_{cor,avg}$ [lx]
$E_{cor,avg(i)}$	The indirect portion of $E_{cor,avg}$ [lx]
MRSE	Mean room surface exitance [lm/m^2]
R^2	Coefficient of determination
RMSE	Root mean square error
WWR	Window-to-wall ratio
ρ	The reflectance of the surface where the first reflection occurs
ρ'	The area-weighted average of room surface reflectance
$\rho_{ceiling}$	The reflectance of ceiling
ρ_{floor}	The reflectance of floor
ρ_{wall}	The reflectance of wall
ρ_{window}	The reflectance of window
Φ	The initial flux from luminaires [lm]

technical report 218: 2016 [4]). Therefore, it is important to explore efficient and practical ways to enhance corneal illuminance in indoor lighting.

Based on studies from different research groups, a wide range of corneal illuminance were proposed as the required amount for sufficient circadian effect [16]. This is partially due to the fact that lighting's circadian effect depends on not only corneal illuminance, but also other factors such as spectral power distribution (SPD), timing, duration, and prior lighting exposure history [4–7]. Currently, there are already models proposed to quantify lighting's circadian impact, among which the *Circadian Stimulus* (CS) model [7,22–24] and the *Equivalent Melanopic Lux* model [5,25,26] are two popular ones. Take the CS model developed by Rea et al. as an example, it first calculates the *circadian light* (CL_A) [22] based on the spectral irradiance distribution at cornea, and then obtain the value of CS based on CL_A, assuming 1 h exposure and a fixed, 2.3 mm diameter pupil [7,23,24]. The value of CS is designed to be equal to the percentage of melatonin suppression [7]. Therefore, it can be used to explicitly quantify lighting's circadian impact. From studies with Alzheimer patients, office staff, teenagers, healthy older adults, and submariners, a lighting intervention delivering a CS value of at least 0.3 during the early part of the day can effectively improve circadian entrainment and sleep quality [16,27,28]. Besides, a CS level of 0.35 was proposed as "sufficient to promote daily entrainment" in a hospital environment [10].

Among the lighting factors that affect circadian stimulation, SPD and corneal illuminance are two "static" factors [13] that are typically decided by lighting designers, while the "non-static" factors, such as timing, duration, and prior lighting exposure history, are usually up to the end-users to decide. Studies show that daylight spectrum is relatively efficient in providing circadian stimulus: based on the CIE D65 spectrum, a corneal illuminance of 233 lx corresponds to a CS value of 0.35 [10,17]; however, artificial light sources that are typically used in indoor applications can be much less effective in delivering CS: for the same CS target of 0.35, the corresponding corneal illuminance needed for a 4000 K FL11 fluorescent lamp is 575 lx [17]. LED spectral optimization is currently an active research area which aims to maximize the tunability range of circadian effect under the constraints of general lighting requirements, such as white color, a high color rendering index (CRI), and a suitable range of correlated color temperature (CCT) [17,29–31]. Our study shows that even with advanced LED spectral optimization, a minimum corneal illuminance of 442 lx is needed for the CS target of 0.35, given the constraints of 4000 K CCT and CRI ≥ 80 [17]. One finds that the required corneal illuminance values are several times higher than that is recommended/achieved in current lighting-design practices. Therefore, applying circadian light in the built environment places a very challenging requirement on corneal illuminance during the daytime.

The overall corneal illuminance can be divided into two portions: (i) direct corneal illuminance, which is contributed by the light arriving at eyes directly from light sources, and (ii) indirect corneal illuminance, which is caused by the inter-reflected light that goes through at least one reflection in the room before reaching the eyes. The preferred ratio of direct/indirect components is different between lighting for visual tasks and lighting for non-visual circadian effect: The former typically prefers a high percentage of direct component to achieve high energy efficiency, while the latter, illuminance at eyes, prefers a high percentage of indirect component for avoiding discomfort glare. For artificial lighting, the initial flux, the intensity distribution from luminaires, and the reflectance of room surfaces are parameters believed to be important to indirect corneal illuminance; for daylighting design, the window-to-wall ratio (WWR) and surface reflectance are important factors. The analysis above can be summarized in Fig. 1.

In recent years, efforts have been made towards good lighting design for corneal illuminance. For example, the optimization of the direct/indirect ratio of light distribution from luminaires was discussed to improve corneal illuminance [28]; CS autonomy (the "circadian counterpart" of daylight autonomy) [10] based on corneal illuminance was studied with different lighting factors such as latitude, weather, window-to-facade ratio, distance from the window, and interior surface reflectance [10,11]; field evaluations of corneal illuminance were carried out to find circadian stimulus potential of daylit and non-daylit spaces in dementia care facilities [32]. These studies provided potential approaches to improve corneal illuminance in indoor spaces, however, to the best of our knowledge, no theory was formed to explicitly describe the dependence of corneal illuminance on important lighting factors. Such theoretical formulas would be very valuable for guiding circadian lighting design.

In this work, first, rule-of-thumb equations are proposed to guide circadian lighting design with a focus on indirect corneal illuminance, for both artificial lighting (with and without windows) and daylighting scenarios. The simple equations could provide quick feedback for lighting design at the field. Second, the proposed equations are validated by comparing their predications against numerical simulation data obtained based on the Radiance software, under various lighting conditions (different combinations of room surface reflectance, initial light distribution, and WWR for artificial lighting; and different combinations of surface reflectance, WWR, and geographic location for daylighting). Third, based on the proposed equations and numerical simulation data, factors that could improve corneal illuminance are compared to find the dominant one for both artificial lighting and