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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, $E_{\text{cor,avg (i)}} = (\Phi/C_1)\cdot \rho/(1-\rho')$, where $E_{\text{cor,avg (i)}}$ 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, $E_{\text{cor,avg (i)}} = C_2 \cdot \text{WWR} \cdot \rho/(1-\rho')$, 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

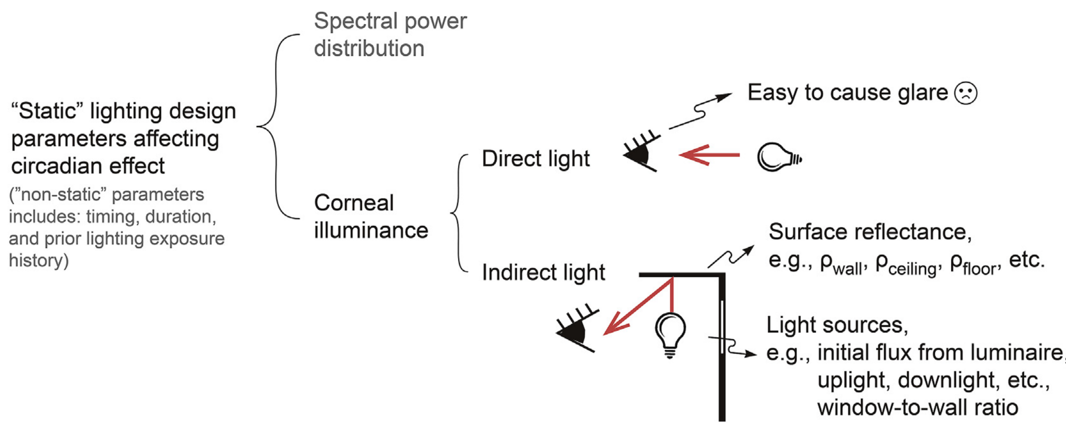

Fig. 1. Lighting design parameters affecting circadian effect.

daylighting scenarios. The outcome of this research can be applied to guide circadian lighting design and explore effective approaches to enhance corneal illuminance in the built environment.

2. Rule-of-thumb equations

An existing theory that is relevant to the corneal illuminance contributed by inter-reflected light is the concept of mean room surface exitance (MRSE) proposed by Cuttle [1,2,33,34]. MRSE is defined as the average density of luminous flux exiting all surfaces within the room and was used to evaluate perceived brightness (or dimness) of ambient illumination [1,2,33,34]. Cuttle hypothesized that an approximate value of MRSE could be obtained by "taking up a position that brings most of the space into view, holding an illuminance meter vertically at eye level, and shielding it from direct light while taking a reading" [2]. While this hypothesis implies that indirect corneal illuminance, if taken properly, should be similar to MRSE, no proof or disproof were reported to the best of our knowledge. Besides, Cuttle's model is based on a windowless room.

It is believed by the authors that such a measured value of indirect corneal illuminance should vary with the location in the room and the eye-sight direction, but the average value over the entire room and all eye-sight directions, at either standing or sitting position, could be comparable to the average density of flux exiting all the room surfaces. This average value of indirect corneal illuminance, denoted as $E_{cor,avg\ (i)}$, is also directly relevant to the level of circadian stimulus provided by indoor lighting. Therefore, by performing an analysis enlightened by Cuttle's MRSE work [1], theoretical equations are presented to describe the dependence of $E_{cor,avg\ (i)}$ on room surface reflectance, for both artificial lighting and daylighting:

For artificial lighting, assuming that the initial flux from a luminaire is Φ, and the reflectance of the room surface where the first reflection occurs is ρ, then $\Phi \cdot \rho$ is the initial indirect flux generated after the first reflection. ρ′ is denoted as the weighted average of reflectance over the entire room surfaces, then the additional indirect flux generated from the 2nd, 3rd, 4th, …reflections can be approximated as $\Phi \cdot \rho \cdot \rho'$, $\Phi \cdot \rho \cdot \rho'^2$, $\Phi \cdot \rho \cdot \rho'^3$, …, respectively. Therefore, the overall inter-reflected flux, which is the summation of the terms above (geometric progression), can be expressed as $\Phi \cdot \rho/(1-\rho')$. Given a fixed overall flux, average indirect corneal illuminance decreases with increasing total surface area A, therefore, the following equation is proposed to be tested:

$$E_{cor,\ avg\ (i)} = \frac{\Phi}{C_1} \cdot \frac{\rho}{1-\rho'} \tag{1}$$

where C_1 is a constant that is comparable to A, and can be lightly affected by factors such as initial light distribution from luminaires, luminaire location, and room geometry, etc. The weighted average of reflectance over the entire room surfaces, ρ′, can be expressed as follows:

$$\rho' = \frac{\rho_{wall} \cdot A_{wall} + \rho_{ceiling} \cdot A_{ceiling} + \rho_{floor} \cdot A_{floor} + \rho_{window} \cdot A_{window}}{A} \tag{2}$$

where A_{wall}, $A_{ceiling}$, A_{floor}, and A_{window} represent the surface area of wall (window area excluded), ceiling, floor, and window, respectively. Therefore, $A_{wall} + A_{ceiling} + A_{floor} + A_{window} = A$; ρ_{wall}, $\rho_{ceiling}$, ρ_{floor} and ρ_{window} are the corresponding surface reflectance.

Equations (1) and (2) can be used for scenes with a window, by treating the light going through the windows to the outside as being absorbed. For example, if the window area doesn't contain any glass and all the light hit the window area from inside goes outside, $\rho_{window} = 0$ should be applied.

For daylighting, the initial flux coming into the room is proportional to the window-to-wall ratio. Therefore, the following equation is proposed to be tested:

$$E_{cor,avg\ (i)} = C_2 \cdot \mathrm{WWR} \cdot \frac{\rho}{1-\rho'} \tag{3}$$

where C_2 is a constant determined by factors such as the daylight condition outside the room, the direction of the window, and the total room surface area, etc. Eq. (3) indicates that there are two effects induced by an increase in window size: WWR increases proportionally with window size, and ρ′ in general decreases by following Equation (2): for the increased window area, ρ_{wall} is replaced by ρ_{window}.

The rule-of-thumb equations (1) and (3), if tested to be accurate, can be used to describe the dependence of average indirect corneal illuminance on room surface reflectance, which is a simple but valuable tool to guide practical circadian lighting design. In the following sections, the proposed equations are verified by comparing to numerical simulation data obtained with the Radiance software, under various lighting conditions, which include the cases of:

- Artificial lighting: a windowless room, same reflectance for all surfaces (ρ = ρ′), various surface reflectance and initial light distributions;
- Artificial lighting: a windowless room, different combinations of ceiling, wall, and floor reflectance (ρ ≠ ρ′);
- Artificial lighting: a room with a window (ρ ≠ ρ′), various WWRs and surface reflectance;
- Daylighting: a room with a window (ρ ≠ ρ′), various surface reflectance, WWRs, and geographic locations.

3. Methodology

This section describes the detailed parameters used in lighting simulation.

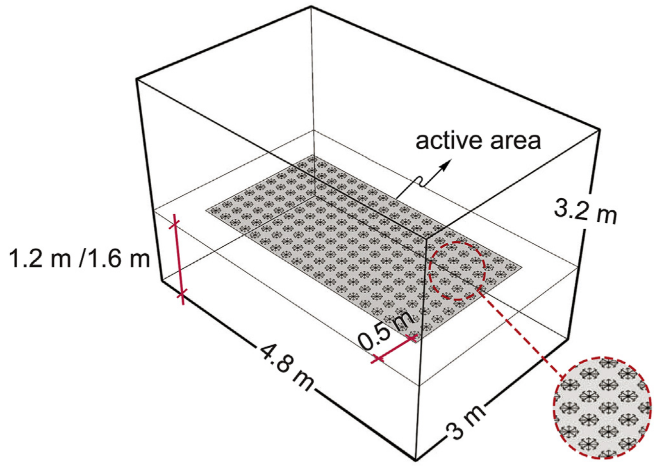

Fig. 2. A sketch of the room model and the calculation grid.

3.1. Room setting

A virtual room measuring 3.0 m wide × 4.8 m deep × 3.2 m high is adopted. The setting that the length of the room is 1.6 times the width follows the model setting in CIE 52 1982 [35]. The inner surface of the room is assumed to be ideally diffusive. In this work, the effect of furniture on luminous environment and spectral reflectance of surfaces [36,37] are not discussed.

3.2. Simulation software

Visualized in the 3-D modeling software Rhinoceros [38], the room geometry is modeled in Grasshopper [39], where the simulation procedure can use the open-source plugins Honeybee and Ladybug to connect to the Radiance software for lighting simulation. The daylighting simulation is performed using DAYSIM, which is a Radiance-based software [40,41].

3.2.1. Simulation grid

As shown in Fig. 2, a horizontal measurement grid is positioned at 1.2 m or 1.6 m above the floor to represent eye locations when at sitting or standing positions, respectively [3,12]. A zone of 0.5 m wide from the wall is excluded from calculation, due to the fact that people are not likely to stay within this zone for a long time. The "active area" of the room is then defined, as illustrated in the figure. Within this area, the measurement points are chosen to have a 0.2 m spacing. For the following numerical simulations, the corneal illuminance at a measurement point (mean value of eight eye-sight directions) is denoted as E_{cor}, with its direct and indirect portions denoted as $E_{cor\ (d)}$ and $E_{cor\ (i)}$, respectively; the average E_{cor} value of all the measurement points within the active area is denoted as $E_{cor,avg}$. The direct and indirect portions of $E_{cor,avg}$ are denoted as $E_{cor,avg\ (d)}$ and $E_{cor,avg\ (i)}$, respectively.

3.2.2. Radiance parameters

Radiance is a well-proven lighting simulation software [42–44]. The calculation parameters adopted in simulations are listed in Tables 1 and 2. The meaning of the parameters can be found in Refs. [45,46]. Among the parameters, ambient bounce (ab) is an important one, because it defines the number of reflections, which affects both simulation time and accuracy. To balance the two important aspects, the criterion of $\rho^{ab} < 1\%$ is adopted to determine the desired number of reflections (in addition, ab ≥ 6 is required). This criterion ensures that only less than 1% of the initial flux is neglected. Therefore, the error of overall corneal illuminance caused by this approximation is less than 1%. The value of "ab" used under various surface reflectance settings to calculate E_{cor} are shown in Table 2.

Table 1
Model Radiance parameters.

Parameters		
as = 1024	lr = 50	sj = 0
ar = 64	lw = 0	dp = 1024
aa = 0.0	ds = 0.02	dc = 1
av = 0	dj = 0	dr = 6
pt = 0	pj = 1	dt = 0
ps = 1	st = 1	ad = 4096

Table 2
Ambient bounce values used to calculate E_{cor} at different room surface reflectance.

ρ	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
ab	6	6	10	10	10	20	30	50

For artificial lighting, a setting of "ab = 0" turns the reflection calculation off [46]. Therefore, the direct corneal illuminance $E_{cor\ (d)}$ can be calculated under this setting, while the indirect portion can be obtained by $E_{cor\ (i)} = E_{cor} - E_{cor\ (d)}$; for daylighting simulation, light going through the windows from outside is already counted as one ambient bounce in the software [46]. Therefore, the direct corneal illuminance is calculated under the setting of "ab = 1".

4. Validation of the proposed equations

Next, we compare the proposed equations with simulation data under various lighting conditions.

4.1. Artificial lighting: a windowless room, same reflectance for all surfaces (ρ = ρ′); various surface reflectance and initial light distributions

The simplest lighting scene is investigated first: a windowless room with wall, ceiling, and floor having the same surface reflectance (ρ = ρ′). A "downlight" luminaire with flux of 3142 lm and a Lambertian distribution is placed at the center position of the ceiling. Within the active area, the average direct corneal illuminance $E_{cor,avg\ (d)}$ and average indirect corneal illuminance $E_{cor,avg\ (i)}$ at both 1.2 m height and 1.6 m height are calculated at various surface reflectance ρ, as shown below:

Fig. 3 shows that the average direct corneal illuminance remains constant at 22.5 lx for 1.2 m height and 33.9 lx for 1.6 m height, while the average indirect corneal illuminance increases dramatically with the increasing surface reflectance. The indirect portion surpasses the direct portion at a low reflectance value of about 0.4 and becomes significantly higher than the direct portion at higher reflectance values. For example, at a reflectance value of 0.8 and eye height of 1.2 m, the $E_{cor,avg\ (i)}$ value is 168.2 lx, which is 7.5 times of the corresponding $E_{cor,avg\ (d)}$ value. This result shows that inter-reflected light can play a dominant role in providing high corneal illuminance for circadian lighting applications besides its benefit of avoiding discomfort glare.

The best fit of Eq. (1) to the indirect corneal illuminance data (for both 1.6 m and 1.2 m heights) is shown by the dashed curve in Fig. 3(b), with the constant $C_1 = 76.2\ m^2$. The corresponding coefficient of determination (denoted as R^2), index of agreement (denoted as d), and root mean square error (RMSE) are 0.9992, 0.9998, and 3.2 lx, respectively, which indicate a very good fitting. Therefore, in this particular case, the proposed simple equation can be easily used to guide lighting design for corneal illuminance. For example, based on Eq. (1), one can easily estimate (even by mental arithmetic) that when the reflectance is improved from 0.5 to 0.8, the average indirect corneal illuminance is increased to 4 times of the original value. While a careful Radiance simulation shows the change is actually 3.8 times (for both

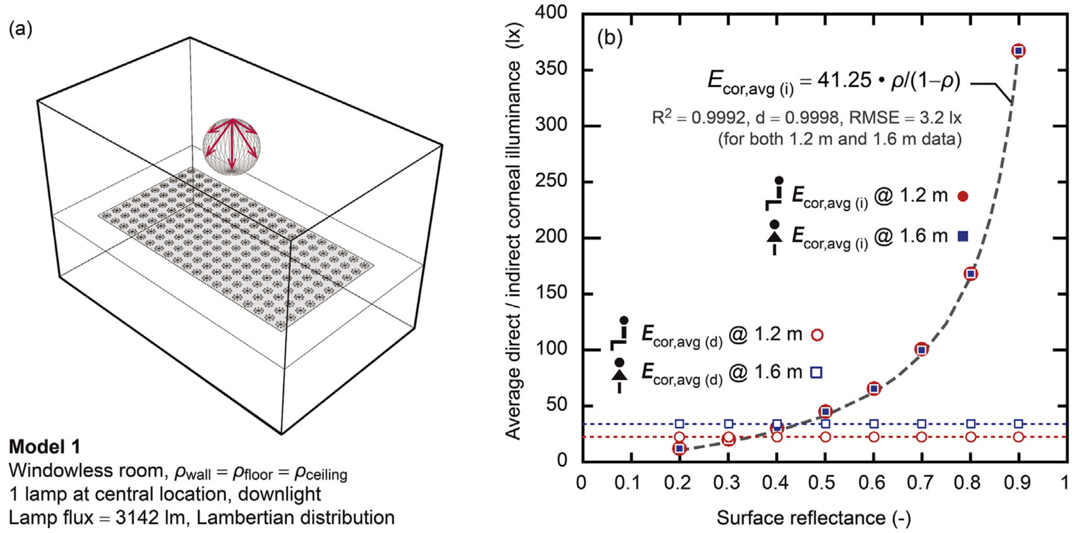

Fig. 3. (a) A sketch of simulation model and (b) average direct/indirect corneal illuminance at various surface reflectance, for both 1.2 m and 1.6 m heights.

1.2 m and 1.6 m heights), the rule-of-thumb equation provides a very simple and insightful method for lighting designers to estimate corneal illuminance at the field, and also shows a big potential for significant energy saving by just painting the room. It is found that the $E_{cor,avg\ (i)}$ values at 1.6 m and 1.2 m heights are very close. Therefore, we just concentrate on the eye height of 1.2 m for sitting positions in the rest part of this paper unless otherwise noted.

In order to investigate the effects of initial light distribution on indirect corneal illuminance, the values of $E_{cor,avg\ (i)}$ are compared for the following four lighting scenes, as shown in Fig. 4(a): one lamp at the central location, downlight (Model 1), Fig. 4(b): one lamp at the central location, uplight (Model 2), Fig. 4(c): one lamp at an off-centered location (in this case, the distances to the two nearest walls are 0.8 m and 1.6 m), uplight (Model 3), and Fig. 4(d): six lamps at a separated pattern, uplight (Model 4). In each case, the total initial flux coming out of the lamp(s) is 3142 l m; for those with uplight setting, the lamp is suspended 0.8 m from the ceiling. The average indirect corneal illuminance of the entire active area versus room surface reflectance are plotted for the four lighting scenes, as shown in Fig. 4(e). It is found that although the value of $E_{cor,avg\ (i)}$ various under different settings of luminaire location and intensity distribution, the four groups of data in general follow the same trend defined by Eq. (1) with the constant $C_1 = A = 78.7\ m^2$, as shown by the dashed curve. Among the Models 1–4, the luminaire location (centered vs. off-centered vs. separated) and initial light distribution from luminaires (uplight vs. downlight) are changed significantly, but only a small impact on average indirect corneal illuminance is observed. This result clearly shows that the initial light distribution has a much less impact compared to surface reflectance when designing for circadian light − as long as the reflectance of the first reflection remains the same. Even the amount of initial flux from luminaires is not as effective as surface reflectance in providing a high indirect corneal illuminance: the dependence of $E_{cor,avg\ (i)}$ on initial flux is linear, while its dependence on room surface reflectance is super-linear. Therefore, surface reflectance is the key factor towards a high indirect corneal illuminance.

The distributions of corneal illuminance over the active area at reflectance of 0.8 and 1.2 m height are shown below. Note that only Model 1 contains direct portion, therefore Fig. 5(a), 5(c), 5(d), and 5(e) can represent the distributions of overall corneal illuminance for Models 1–4, respectively, while Fig. 5(b), 5(c), 5(d), and 5(e) can represent the distributions of indirect corneal illuminance for Models 1–4, respectively. The uniform distributions of corneal illuminance mainly come from the high surface reflectance, instead of luminaire location or initial light distribution. This is a valuable feature to ensure the entire

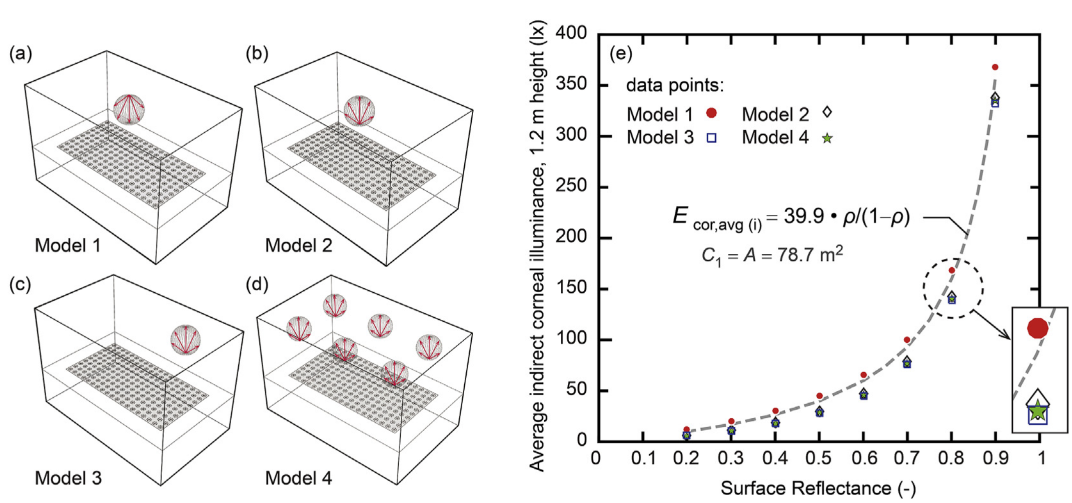

Fig. 4. (a)–(d) Sketches of simulation models 1 to 4 and (e) average indirect corneal illuminance at various surface reflectance for each model, at eye-height of 1.2 m.

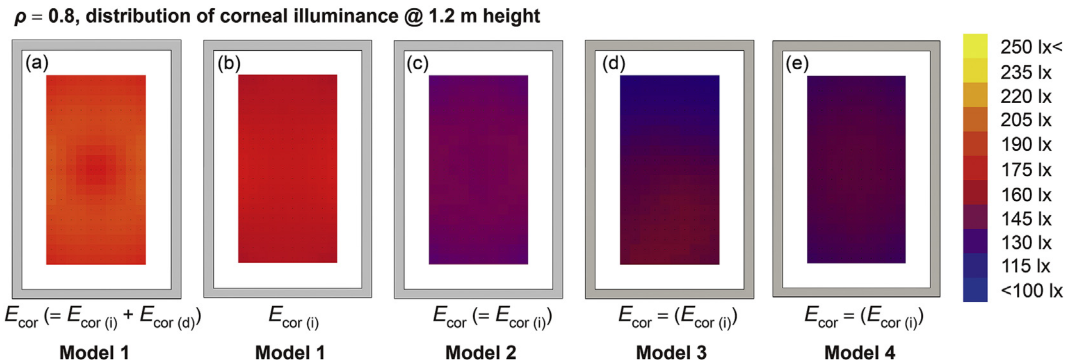

Fig. 5. The distributions of corneal illuminance within the active area, at reflectance of 0.8 and 1.2 m height.

active area being covered with a sufficient level of circadian stimulus.

4.2. Artificial lighting: a windowless room, different combinations of ceiling, wall, and floor reflectance ($\rho \neq \rho'$)

Next, more general scenes are investigated, where the reflectance of wall, ceiling, and floor can be different ($\rho \neq \rho'$). To compare the numerical simulation data with Eq. (1), we take the setting of one lamp at central location & uplight (as Model 2) as an example, but modified the intensity distribution of the lamp to a truncated Lambertian distribution, as shown in Fig. 6. Such a modification ensures that the first reflection always occurs at the ceiling, therefore Eq. (1) can be easily calculated for various combinations of ρ_{wall}, $\rho_{ceiling}$, and ρ_{floor}. The overall flux coming out of the lamp is still fixed at 3142 lm.

To select reasonable combinations of ρ_{wall}, $\rho_{ceiling}$, and ρ_{floor} that are likely to be adopted in real applications, EN12464-1 2011 [3] is referred to for recommended range of surface reflectance, which is shown in Table 3.

Three levels of wall reflectance values (0.4, 0.6, and 0.8), three levels of ceiling reflectance values (0.4, 0.6, and 0.8), and two levels of floor reflectance values (0.2 and 0.4) are selected. A total of 18 (= 3 × 3 × 2) combinations can be formed, which is reasonably consistent with the recommended range in Table 3. The detailed list of combinations is shown in Table 4.

The above data set of $E_{cor,avg\ (i)}$ versus $\rho/(1-\rho')$ is plotted in Fig. 7 (marked as open circles; Model 5), together with the data set from Model 2 (marked as solid squares). The dashed line in Fig. 7(b) is the best fit of Model 2 data using Eq. (1), with the constant $C_1 = 85.4\ m^2$. It is found that by allowing $\rho \neq \rho'$, the result in general still follows the same trend (the dashed line) defined by the data of Model 2, in which the wall, ceiling, and floor have the same reflectance. One finds that the data of Model 5 can be slightly below the dashed line, which can be explained as follows: in the deduction of Eq. (1), it is assumed that the light after first reflection sees an average reflectance of ρ', however, in reality, the second reflection cannot occur at the ceiling, which in most cases has a reflectance above the average. Therefore, the "effective" average reflectance can be slightly lower than ρ' and Eq. (1) can overestimate the indirect corneal illuminance when the ceiling reflectance is much higher than the average reflectance. Nevertheless, the result in Fig. 7(b) still shows a reasonable accuracy for a simple rule-of-thumb equation which can provide quick design feedback at the field.

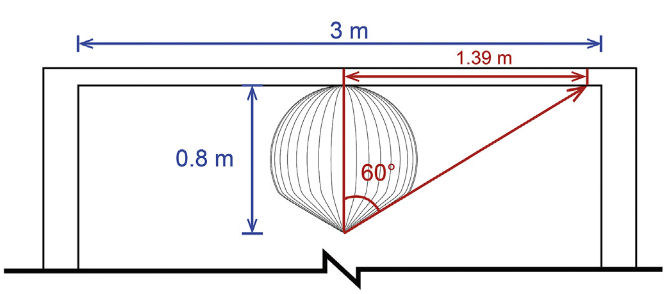

Fig. 6. Truncated Lambertian distribution.

Table 3
Recommended values of room surface reflectance from EN12464-1 2011.

Surface	Reflectance range
Ceiling	0.7 to 0.9
Walls	0.5 to 0.8
Floor	0.2 to 0.4

4.3. Artificial lighting: a room with a window ($\rho \neq \rho'$), various WWRs and surface reflectance

One step further, the model is expanded to include a window. In order to avoid the complexity of exploring glass types with different reflectance, the extreme case of no glass (all the light hit the window area from inside goes outside) is adopted. This can be treated as the window area having a surface reflectance of 0 during the process of calculating ρ' in Equation (2). The WWR setting, the reflectance setting, and the corresponding numerical simulation data are shown in Fig. 8. The dashed line is the best fit of the data in Model 2 (a windowless room). Again, it is found that by allowing a window in the model, the simulation result still follows the original trend.

The models above are for artificial lighting scenarios. Next, Eq. (3) is compared with numerical data obtained from daylighting simulation.

Table 4
Combinations of ρ_{wall}, $\rho_{ceiling}$, and ρ_{floor} values used in simulation.

ρ_{wall}	$\rho_{ceiling}$	ρ_{floor}	ρ'	$\rho/(1-\rho')$	$E_{cor,avg\ (i)}$ @1.2 m (lx)
0.4	0.4	0.2	0.36	0.63	17.86
0.4	0.4	0.4	0.40	0.67	19.80
0.4	0.6	0.2	0.40	1.00	27.37
0.4	0.6	0.4	0.44	1.06	30.50
0.4	0.8	0.2	0.44	1.42	37.30
0.4	0.8	0.4	0.47	1.52	41.80
0.6	0.4	0.2	0.49	0.78	24.64
0.6	0.4	0.4	0.53	0.85	27.94
0.6	0.6	0.2	0.53	1.27	38.33
0.6	0.6	0.4	0.56	1.37	43.80
0.6	0.8	0.2	0.56	1.83	53.34
0.6	0.8	0.4	0.60	2.00	61.54
0.8	0.4	0.2	0.62	1.04	35.52
0.8	0.4	0.4	0.65	1.15	41.63
0.8	0.6	0.2	0.65	1.73	57.02
0.8	0.6	0.4	0.69	1.94	67.72
0.8	0.8	0.2	0.69	2.58	81.72
0.8	0.8	0.4	0.73	2.93	98.78

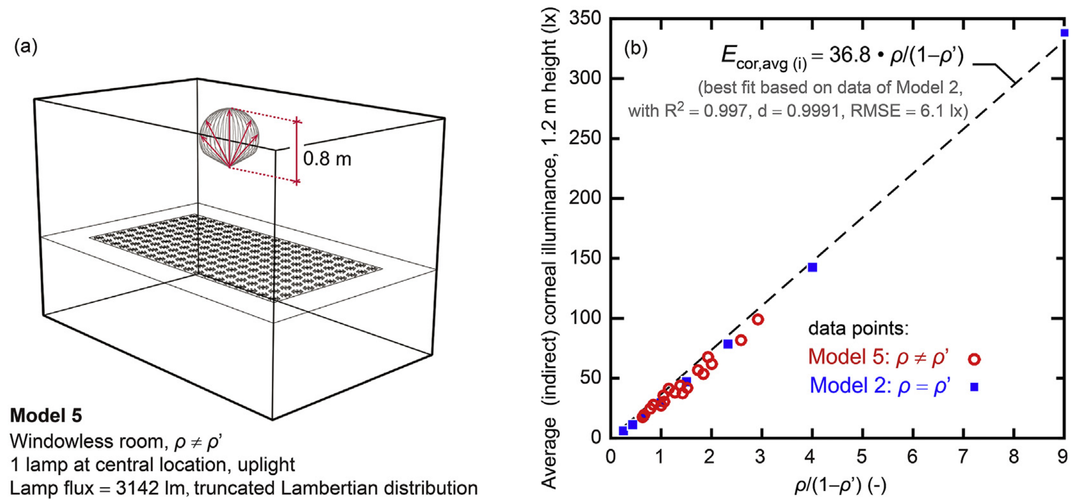

Fig. 7. (a) A sketch of simulation model and (b) average (indirect) corneal illuminance versus $\rho/(1-\rho')$.

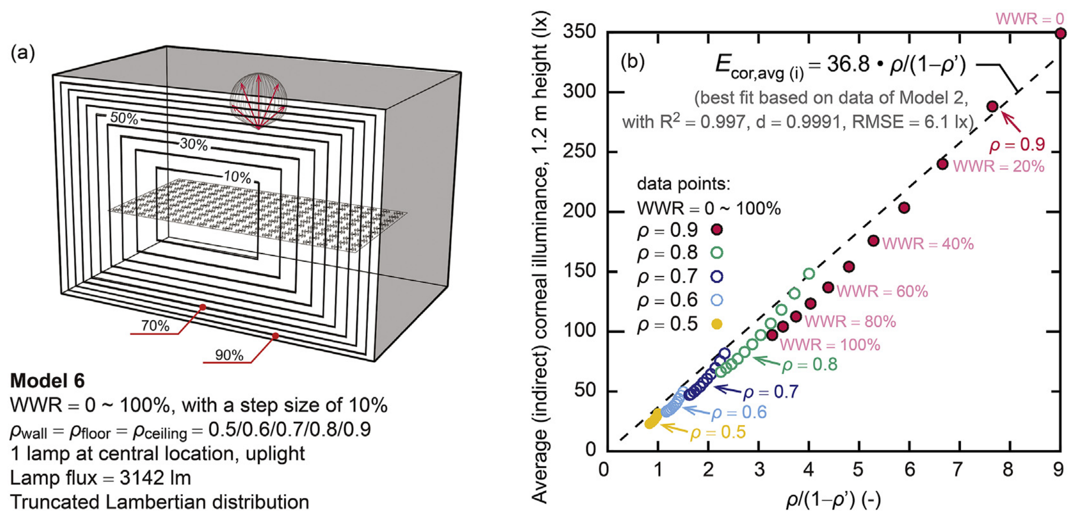

Fig. 8. (a) A sketch of simulation model and (b) the average (indirect) corneal illuminance versus $\rho/(1-\rho')$.

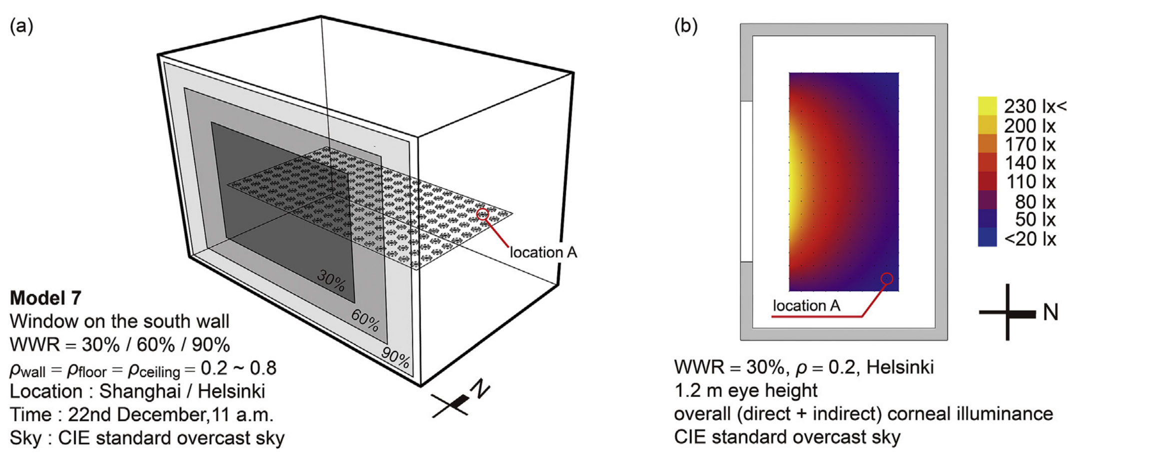

Fig. 9. (a) A sketch of simulation model and (b) the distribution of overall corneal illuminance at the setting of WWR = 30%, ρ = 0.2, and Helsinki.

4.4. Daylighting modeling: various surface reflectance, WWRs, and geographic locations

The following daylighting simulations are conducted by using the CIE standard overcast sky model, which represents densely overcast weather condition and is one of the most frequently used type [47,48]. In this work, 11 a.m. of December 22nd (the winter solstice) is selected as the time setting because the amount of daylight is most likely to be insufficient on this date of the year, and morning hours is critical when considering light's circadian impact. A sketch of the room model is

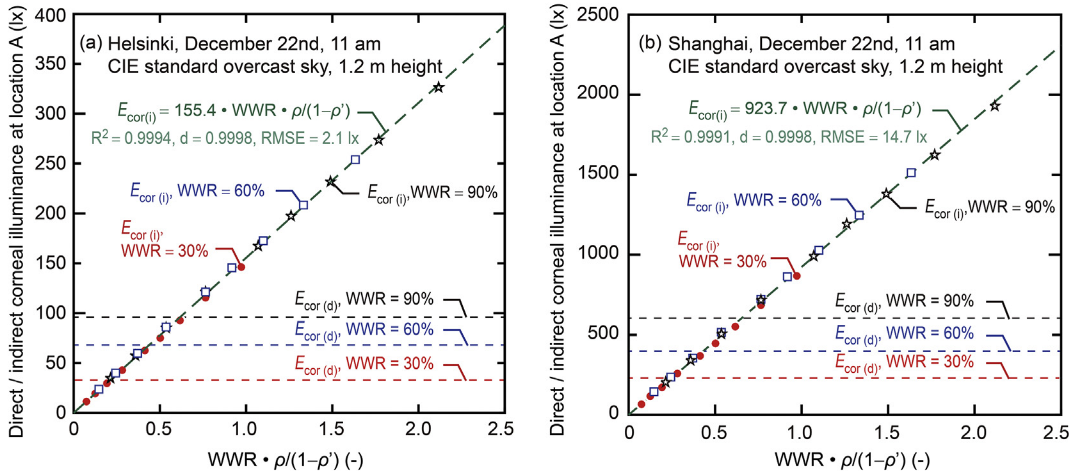

Fig. 10. Direct & indirect corneal illuminance at location A versus WWR $\cdot$ $\rho/(1-\rho')$ for (a) Helsinki and (b) Shanghai.

shown in Fig. 9(a). The locations of Helsinki and Shanghai are chosen because the former represents a high-latitude place and the latter is the place where the authors locate.

As an example, Fig. 9(b) shows the distribution of overall (direct + indirect) corneal illuminance E_{cor} within the active area, with the setting of WWR = 30%, $\rho = 0.2$, and the location of Helsinki. As mentioned earlier, Daylight (D65 spectrum assumed) with an E_{cor} of 233 lx can be considered sufficient for circadian stimulus [10,17], which is found to be achievable in the area near the window. Indeed, at near-window area, E_{cor} is mainly contributed by the direct light from outside. Therefore, sufficient circadian stimulus can be achieved even at low room surface reflectance; while at areas away from the window, such as the "location A" marked in Fig. 9, the corneal illuminance is mainly contributed by the indirect light which goes through at least one reflection in the room. In this particular case, the corneal illuminance at location A is 48 lx, which is much less than 233 lx and therefore is considered insufficient for daily circadian entrainment. A good circadian lighting design should ensure that most of the active area is covered with the desired quantity of diffused light. For the locations deep into the room, higher surface reflectance and a higher window-to-wall ratio are potential approaches to improve corneal illuminance.

The combinations of three levels of WWR (30%, 60%, 90%) and nine levels of surface reflectance values (0.2, 0.3, 0.4, 0.5, 0.6, 0.65, 0.7, 0.75, 0.8) are explored. First, both direct and indirect portions of corneal illuminance at location A are calculated and plotted as a function of WWR $\cdot$ $\rho/(1-\rho')$, for locations of Helsinki and Shanghai.

It is shown in Fig. 10 that the direct portion of corneal illuminance is only related to WWR, while the indirect portion can be influenced by both WWR and surface reflectance. Applying a linear regression to the numerical data set of $E_{cor\ (i)}$-versus-WWR $\cdot$ $\rho/(1-\rho')$ results in excellent fits, as shown by the dashed lines in both Fig. 10(a) and (b), with R^2 values of 0.9994 and 0.9991, respectively. The excellent fits indicate that Eq. (3) is a good approximation to predict the impacts of WWR and surface reflectance on indirect corneal illuminance in daylighting designs. It is shown that for Shanghai, a CS of 0.35 (or corneal illuminance of 233 lx) can be easily achieved, while for Helsinki, achieving the same CS target is quite difficult – only at high WWR and ρ values. Note that an increase in window size has two impacts: first, WWR increases

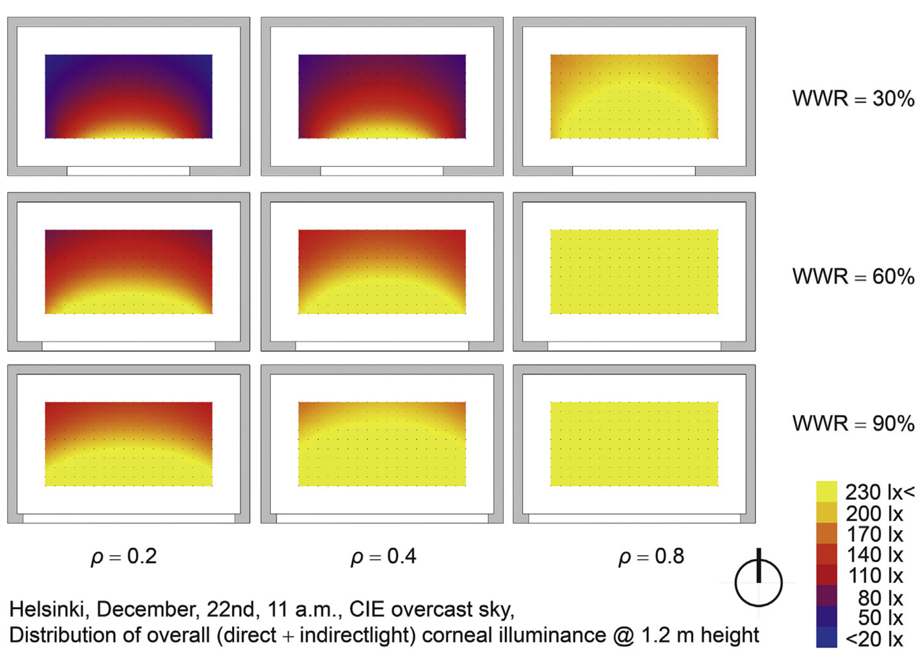

Fig. 11. Distribution of corneal illuminance at various room surface reflectance and window-to-wall ratios, at 11 a.m. of December 22 in Helsinki, under CIE standard overcast sky condition.

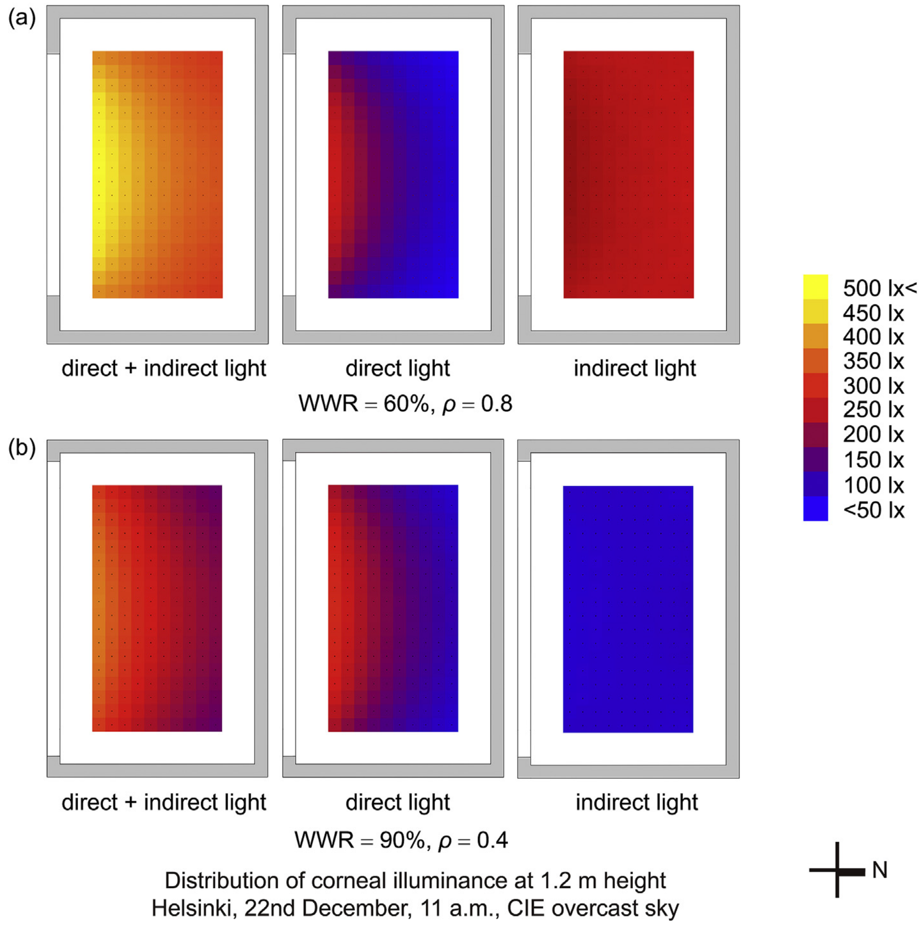

Fig. 12. Distribution of corneal illuminance at (a) WWR = 60%, $\rho = 0.8$ and (b) WWR = 90%, $\rho = 0.4$ for Helsinki at 11 a.m., 22nd December, under CIE standard overcast sky condition.

proportionally to the window size, and second, the effective room surface reflectance ρ' decreases, which can be calculated by using Eq. (2).

Fig. 11 shows the distributions of overall corneal illuminance within the active area at different combinations of WWR and ρ. It can be found that with $\rho = 0.8$, sufficient circadian stimulus can be achieved at most of the active area, even at a relatively small WWR of 30%. Therefore, improving surface reflectance is a practical and effective approach to achieve circadian entrainment in daylighting design.

One can also improve overall corneal illuminance by expanding the window area to a WWR of 90%, but this approach is usually not as convenient as painting the interior surface of the room. Also, the improvement of corneal illuminance by increasing WWR can be mainly contributed by the direct portion. In Fig. 12, the distributions of overall, direct, and indirect corneal illuminance can be compared for the two settings of (a) WWR = 60%, $\rho = 0.8$, and (b) WWR = 90%, $\rho = 0.4$. It is found that the overall corneal illuminance of case (b) is only slightly lower than that of case (a), however, when looking into the indirect component, the $E_{cor\ (i)}$ of case (b) is significantly lower than that in case (a). This result indicates that although the overall corneal illuminance can be improved by expanding the window area, the improvement can mainly come from the direct light, which is easy to cause glare. As indirect corneal illuminance is more favorable in circadian lighting, increasing room surface reflectance should be the most attractive approach.

5. Conclusions

Over the years, indoor lighting design mainly focuses on work-plane illuminance and pays little attention to corneal illuminance. Recently, the importance of indirect corneal illuminance raises because it is critical to lighting functions beyond the traditional visual task performance. Especially, the potential application of circadian lighting in the built environment places a challenging requirement on the level of indirect corneal illuminance during the daytime. As the knowledge increases, it is now realized that the daily light dose received by people in industrialized countries might be too low for the purpose of healthy circadian entrainment. This work aims to develop easy-to-use methods to guide circadian lighting design and explore new approaches to effectively enhance indirect corneal illuminance. The most important contributions can be summarized as follows:

- Simple and insightful equations are proposed to guide circadian lighting with a focus on indirect corneal illuminance, for both artificial lighting and daylighting scenarios. The equations can provide quick feedback for lighting design at the field and promote new concepts of indoor luminous environment for healthy circadian effect;
- The proposed equations are proved to be accurate by comparing their predictions against numerical simulation data obtained from Radiance lighting simulation. Various lighting conditions, including

different combinations of room surface reflectance, initial light distribution, and WWR in artificial lighting and different combinations of surface reflectance, WWR, and geographic location in daylighting, are explored in simulations to validate the equations;

- It is demonstrated that room surface reflectance has a dominant impact on corneal illuminance: with high surface reflectance, the contribution to the corneal illuminance from inter-reflected light can significantly surpass that from direct light, and a uniform distribution of corneal illuminance within the room can be realized; compared to the surface reflectance, the initial light distribution only has a limited impact on indirect corneal illuminance unless it affects the reflectance of the first reflection;
- The approach of improving surface reflectance has significant advantages over other methods such as increasing initial flux from the luminaire (artificial lighting) and expanding the window area (daylighting), because the former (i) more effectively increases indirect corneal illuminance with a super-linear dependence, (ii) only improves the indirect portion of corneal illuminance, which helps avoiding glare, and (iii) does not require additional energy cost or a serious reconstruction (expanding the window area).

Therefore, the proposed rule-of-thumb equations can be a very valuable tool to guide circadian lighting design. Improving room surface reflectance is the recommended approach to achieve quality and efficient circadian lighting.

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