The Nonvisual Effect of Natural Lighting

Xiang Li and Bin Chen

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Abstract

The electromagnetic spectrum within the waveband (~380–780 nm) is defined as light mainly for visual sensation. In addition, the designs of natural light and artificial light are both primarily on basis of the visual demands of occupants. Thus, the minimized constant lighting level is regulated within design standards considering the health risk from radiation. However, people prefer a natural light cycle than a constant one, and the effect of lighting extends much further by recent photobiology researches. The discoveries of the third photoreceptor cell on retina and its neural pathway, which primarily relate to circadian system, indicate that lighting has a significant nonvisual effect on health, mood, and productivity.

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Besides, it strongly suggests that the lighting demand of nonvisual effect is very different from that of the visual one, and artificial lighting is not an appropriate means to satisfy the nonvision system. Nevertheless, daylighting is capable to stimulate both the visual and the nonvisual systems.

To investigate the daylighting environment of Chinese buildings, this paper assessed the nonvisual effect of different design levels in Chinese daylighting design standard (GB/T 50033-2013). As for the evaluation method, the constant relation between vertical illuminance and horizontal illuminance was used to convert the maintained horizontal illuminance of different design levels to the illuminance which reached the eyes (vertical illuminance). Then the nonvisual effect could be calculated by a dose-response function between the nonvisual effect and the illuminance at eyes. Moreover, this function was proposed on basis of the static researches of threshold values which only considered spectrum and intensity. The nonvisual effect of the design levels I-V was respectively 100%, 100%, 71%–100%, 38%–60%, and 5%–16% with the ratio of vertical illuminance to horizontal illuminance varying from 1.5 to 2.0. Since the design standard adopted the overcast sky conditions based on the worst principle, the daylighting of levels I–III was adequate in the major rooms of public buildings where most occupational people stayed during the day considering the actual illuminance which was higher under normal sky conditions. However, if there was a consideration that the aged people who often stayed at home and needed much higher illuminance with the degradation of eye function, the level IV of the daylighting for major residential rooms should be improved. Besides, although the daylighting of level V was extremely low, its effect might be ignored as the short dwell time in transition space. What is more, a field measurement was conducted to validate the evaluation results in a typical room which adopted the design level of III, which demonstrated that the average nonvisual effect of a room in the field measurement was in accordance with the evaluation results mentioned before.

Keywords

Natural lighting · Nonvisual effect · Circadian physiology · Melatonin · Daylighting design · Evaluation method · Vertical illuminance

Introduction

Most occupiers in office buildings prefer the natural light cycle [1]. The physiological mechanism of this phenomenon may be not only for vision but also for nonvision. The natural light can entrain the circadian system of the human body to synchronize with local time by nonvision system [2]. Over the past 10 years, the neural pathway for the nonvision system has become clear after the third photoreceptor cell (ipRPGs) discovered in retina [3]. Because the nonvision system has direct effects on health, mood, and productivity [4], more and more attentions have been paid to the nonvisual effect of lighting environment in recent years. Therefore, this chapter will introduce the biological effect and the mechanism of the nonvision system and then discuss the general design considerations for the nonvisual effect.

The Nonvisual Effect

For more than 150 years, rods and cones were considered as the only photoreceptor cells in eyes. However, the third photoreceptor sell (ipRPGs) was discovered in retina for the nonvision system in 2002 [3]. The nonvision pathway is very different from the vision one where the signals (e.g., shapes and colors) are directly conveyed to the visual cortex in the brain. On the other side, the nonvision signals (e.g., light-dark circle) are conveyed to the pineal gland via SCN (Suprachiasmatic Nucleus) which is the pacemaker of the circadian rhythm. Besides, the nonvision signals in SCN are projected to MFB (Medial Forebrain Bundle) and RF (Reticular Formation) via PVN (Periventricular Nucleus) [4] as shown in Fig. 1. PVN has effects on endocrine, while MFB influences human mood and RF influences the alert level of brain and muscle. Because the nonvisual effect regulates the production of many hormones and other biological mechanisms, the nonvisual effect has significant effects on mood and alertness.

Light primarily regulates the circadian (daily) rhythm and the circannual (seasonal) rhythm of the human body. The circadian rhythm is a basic part of life and operates at a very fundamental level of human physiology. There is an internal oscillator which is used to regulate the time in the brain. The natural light-dark cycle can reset the internal oscillator to entrain the internal clock of the human body to synchronize with the local time with the help of the nonvision pathway and messenger hormones such as melatonin and cortisol. Without the light or other zeitgebers, the internal oscillator will be free-run within about 24.1 h [2] which is slightly longer than the natural cycle of 24 h. Therefore, a hypothesis of the rhythm resonance has been proposed for the considerations of lifespan and well-being [6]. Consequently, the health risk of permanent shift workers is higher in sleep disturbance, premature fatigue, and cardiovascular diseases [7].

In addition, the circadian rhythms of the concentrations of melatonin and cortisol are shown in Fig. 2. Melatonin is a crucial hormone to regulate the wake-sleep

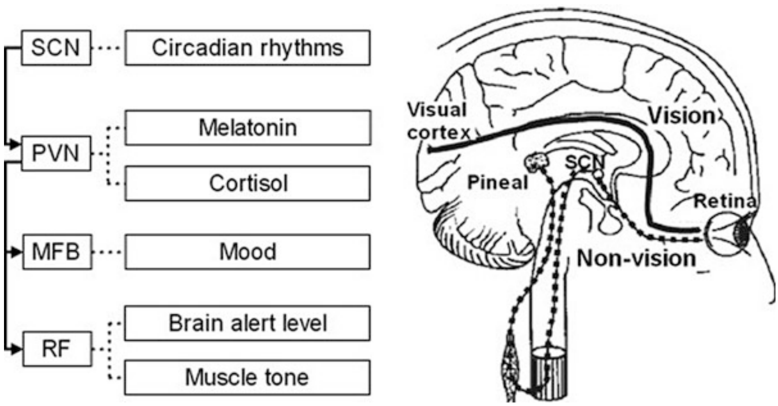


Fig. 1 The neutral pathway of the vision and the nonvision system [4, 5]

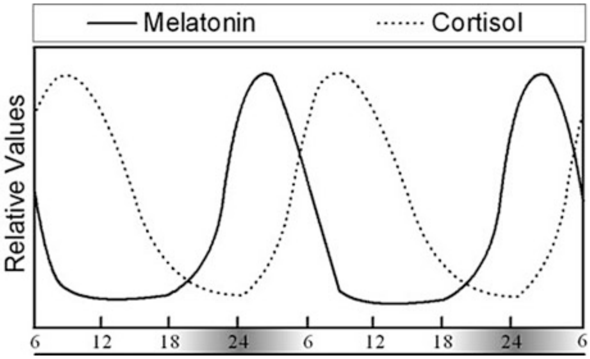


Fig. 2 The circadian rhythms of melatonin and cortisol [8]

rhythm which is a dominant circadian rhythm, while cortisol is the hormone to increase the stress ability of the human body. Besides, exposure to bright environment in the daytime will suppress the secretion of melatonin, which is just the reverse to cortisol. Thus, light exposure has a direct effect on the sleep quality and the arousal level of the body.

Except for the direct impacts on circadian system, mood, and arousal level, the nonvision system has relations to seasonal affective disorder (SAD), cardiovascular diseases (CVD), Alzheimer's disease, cancer, aging, and lifespan. Although the explanations of SAD on basis of circadian system disorder have not been proven, exposure to bright light is an effective treatment [9] which is a therapy not only for SAD but also Alzheimer's disease [10]. Besides, it is reported that sleep distance may cause CVD [11], and the morbidity of CVD is higher for permanent shift workers [7]. On the other hand, it is suggested that the increase of breast cancer is partly due to the suppression of melatonin through light exposure at night [12]. Even, an inappropriate light-dark cycle can accelerate aging process [13] and increase mortality [14]. Therefore, the nonvision system has significant impacts on health and well-being.

On the other hand, the nonvisual effect also has impact on productivity. Many studies of alertness have been conducted under night-shift conditions, because people are highly sensitive to light at night. Fig. 3 shows the effects of two lighting regimes on arousal as a function of the working hours of night-workers [15]. It demonstrates that the arousal level is decreasing after midnight in both settings, but the arousal level under high light exposure is always higher.

Besides, a laboratory study resembles an office environment to investigate the brain-wave pattern (EEG) under different lighting levels, and the results are shown in Fig. 4 [16]. It is revealed that higher lighting levels result in higher arousal levels with fewer delta waves, which is an EEG indicator for sleepiness.

Thus, adequate light exposure during daytime not only has advantages in health and well-being, but also leads to better productivity. It is reported that the productivity for a moderately difficult visual task in an industrial environment may increase 8% when the lighting level is improved from 300 lx to 500 lx, and can be further increased to 20% when the lighting level grows to 2000 lx [17].

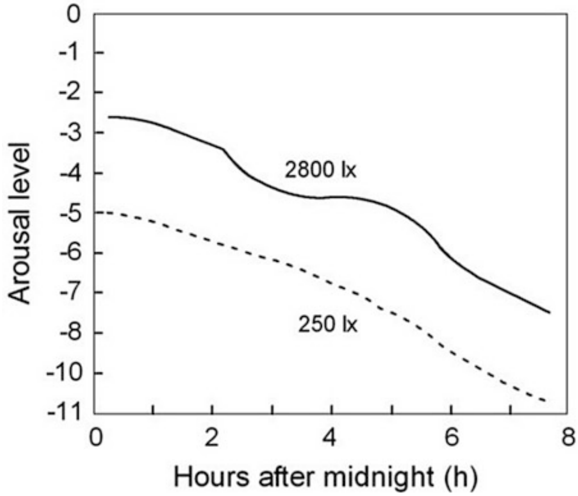


Fig. 3 The arousal levels of the lighting levels of 250 lx and 2800 lx when working after midnight [15]

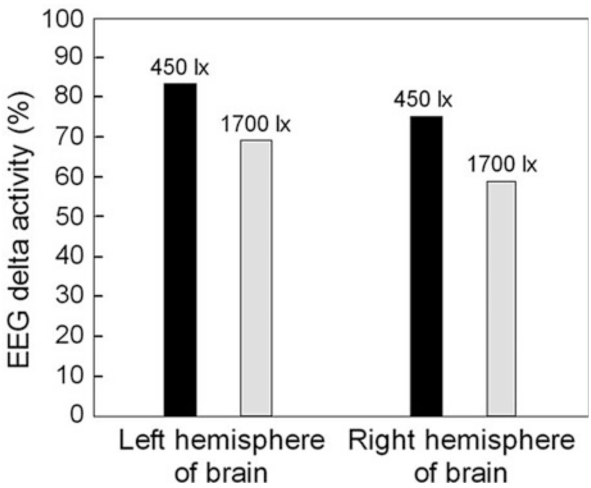


Fig. 4 The delta activity in EEG of office workers under the lighting levels of 450 lx and 1700 lx [16]

The Effect Exposure Factors of Nonvision

Exposure spectrum, timing, intensity, duration, and prior history are the effective factors to entrain the circadian rhythm [18–20]. However, the study of the actual dynamic exposure mechanism is still preliminary when those effective factors are considered, and most studies have been conducted under static condition [18]. Therefore, the existed knowledge about the interactions of exposure time, spectrum, intensity, duration, pattern, and history is incomplete, expecting for further researches. Nevertheless, preliminary design recommendations can be given based on some valid experiment results. Herein, the nonvisual exposure characteristics considered for lighting design are concluded as below:

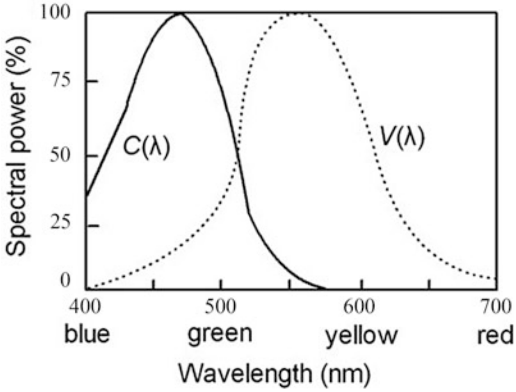


Fig. 5 Spectral responses of the vision system $V(\lambda)$ and the nonvision system $C(\lambda)$ [21]

Light Spectrum

The spectral luminous efficiency curves are different for the vision system and the nonvision system. The vision photoreceptor cell is sensitive to the well-known human photopic curve $V(\lambda)$ which has a peak wavelength at 555 nm, while nonvision cells are sensitive to the melanopsin photopic curve $C(\lambda)$ that has a peak range (446 ~ 477 nm) [21], as shown in Fig. 5.

Besides, the spectrum sensitive of the nonvisual effect may be different with time [22]. Different spectral sensitivity functions of $C(\lambda)$ have been reported in the studies of Kozakov et al. [23] and Thapan et al. [24]. Notwithstanding, the percentage deviations of the circadian efficiency or the circadian faction factor will not exceed 4%, which is calculated on basis of the three different curves $C(\lambda)$ [25].

Exposure Timing

Generally, people need bright environment in the daytime and dim environment in night-time to set the circadian clock to sync with nature environment. Besides, people also need adequate natural light in the daytime to increase body alertness and avoid the phase shifting effect. In addition, about 75% of the population need a daily phase advance for the natural 24 h light-dark cycle, which needs sufficient daylight illuminance exposure at early morning (6:00 ~ 10:00 h) [26, 27]. On the other side, the circadian system is highly sensitive to the light at night, and the bright light exposure at night can delay the circadian rhythm phase of people. The effects of three timings are concluded in Fig. 6.

Exposure Intensity

The dose-response model between light exposure and melatonin suppression is usually utilized to evaluate the nonvisual effect. Fig. 7 respectively shows the dose-response models of D65 daylight and white light for 30 min and 60 min on basis of the human phototransduction model that enables the percentage of melatonin suppression which is due to the calculated illuminance at eyes from any known light source [28]. For the white light, the exposure of 30 lx at eyes for 30 min may be

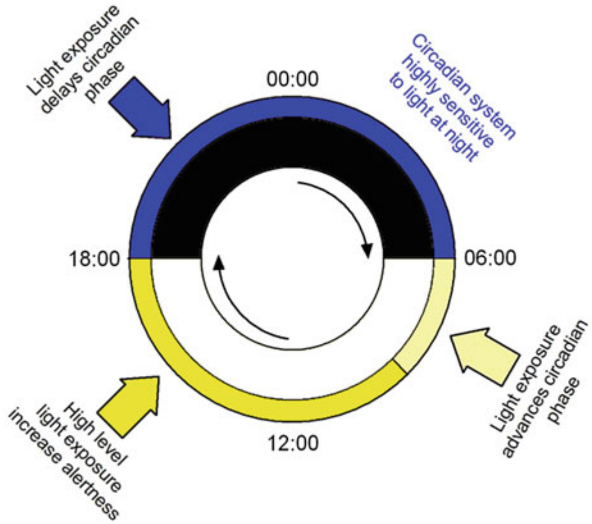


Fig. 6 The effects of exposure timing within 24 h [18]

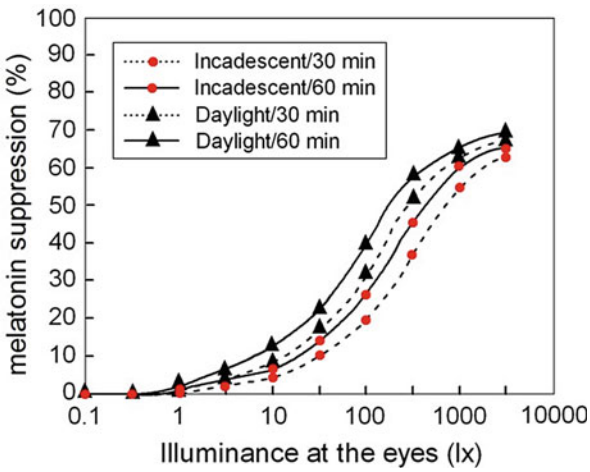


Fig. 7 The predicted dose-response of melatonin suppression under different lighting conditions [29]

the threshold to impact the circadian system [29]. However, the model in Fig. 7 is simplified, and the exact threshold of people is varying with other exposure-response factors such as timing, history, and age.

Besides, people are more sensitive to light in night than in the daytime. The does-effect experiment under Philips Color 840 4100 K fluorescent light in night indicates that people are 100% alert under 300 lx [30]. In addition, dim light (<30 lx) is recommended at night, because it does not disrupt sleep quality [29]. On the other side, a daytime study takes advantage of a mean illuminance of 1056 lx at eyes to evaluate alert effect [31, 32]. Moreover, some researches recommend high natural light exposure for the aged people, or even higher exposure (>2000 lx) for the patients who suffer seasonal affective disorder (SAD) or Alzheimer's disease [10] in the daytime.

Exposure Duration

The duration also has critical influences on how the circadian system is stimulated. The function of exposure duration is nonlinear, so bright light exposure at the start has the greatest melatonin suppression [33]. However, further investigations are needed to determine the exact duration that has the greatest suppression effect.

Given the above, although the inter-dependences among light spectrum, exposure time, intensity, duration, history, and light pattern have not yet been fully uncovered, the rough recommendations of timing, intensity, duration can be concluded in terms of the empirical data in previous studies. Then the preliminary design considerations and the rough evaluation method of the nonvisual effect may be established.

The Lighting Design Considerations of the Nonvisual Effect

Compared with the lighting design for visual tasks, Table 1 gives the general considerations for the design elements of the nonvisual effect. The primary concerns for the nonvisual effect are the well-being and the productivity of the human body. Additionally, the design indexes for the nonvision are different to those of the vision. Thus, the design considerations of the nonvision are much different. There is an example that the design concern of the spatial distribution for the vision is the illuminance uniformity in the field of view to avoid glare and dazzle. However, the design concern of the nonvision is the intensity of the illuminance at eyes in different gaze directions. At the same time, the design concern of color temperature for the vision is to identify the color, while the nonvision has impacts on mood and melatonin suppression. What is more, the efficacies of light illuminance should be carefully considered for different spectral responses of the nonvision. On the other hand, the lighting level for the vision is minimized in design standards to avoid the harm of radiation and visual discomfort, because the exposure demand is static [9]. On the contrary, the exposure demand is dynamic for the nonvision, so the lighting level is maximized in the daytime for high arousal level and minimized at night to avoid the disruption of the wake-sleep rhythm.

Table 1 The design elements for vision and nonvision

Design element	Vision	Nonvision
Purposes	Visual sense and tasks	Well-being and productivity
Objective position	On work plane	At eyes
Timing	Static	Dynamic (bright in daytime and dim at night)
Spectrum	Green yellow	Blue green
Color temperature	Color rendering	Physiological and psychological effect
Lighting level	Minimized	Maximized in daytime and minimized at night
Spatial distribution	Glare and dazzle	Intensity in different gaze directions
Duration	Static	Dynamic (nonlinear)

In details, the exposure timing for healthy people is bright in the daytime and dim at night, but Fig. 6 shows that the people who suffer the delayed phase of the wake-sleep rhythm demand personalized high-level lighting exposure at the early morning to advance the phase. However, light exposure is not recommended at night due to its disruption of sleep quality. Though few people suffer from the advanced phase of the wake-sleep rhythm, they need bright light exposure at night to delay the phase.

Except for timing, the spectrum and the color temperature of lighting illuminance should be carefully considered. Photometry is based on the vision system, but the efficacy of illuminance needs nonvisual convection. Table 2 offers the ratio of circadian rhythm to visual effect for general artificial illuminants [34]. It reveals that the spectrum and the color temperature have impacts on the nonvisual effect. In addition, the circadian system is sensitive to blue LED and the illuminants with high color temperatures.

Compared with artificial illuminants, the spectrum and the color temperature of daylight can both satisfy the lighting demands of the vision and the nonvision as shown in Fig. 8.

For the intensity of illuminance at eyes, many studies recommend over 1000 lx exposure in the daytime and under 50 lx exposure at night, though there is not valid threshold value. Besides, the patients who suffer depression, sleep disorder, and Alzheimer's disease are recommended for higher level light exposure ranging from 2000 lx to 10,000 lx [9]. Obviously, the intensity for the nonvision is much higher than that of the vision in the daytime.

However, the light level at eyes is three to five times lower than that on the work plane under the conventional artificial illuminant mounted on ceiling [37]. Thus, artificial lighting is not appropriate to satisfy the nonvisual effect in the daytime except for the therapy considering economy, energy saving, and visual comfort.

On the other side, the illuminance at eyes is over 1000 lx near the windows in most of the year and may reach to 1000 lx even in the deep of the room with large windows opening [38]. Therefore, it will be return attention to the better daylighting of buildings instead of the alternative electric illuminant only available in last 100 years.

In the daylighting environment, the gaze direction has great effects on the intensity of illuminance at eyes which depends on the portion of bright sky (window) in the visual

Table 2 The efficacy ratios of circadian rhythm to visual effect for general artificial illuminants [34]

Light source	Circadian/visual ratio
4100 K Fluorescent	0.72
2700 K Fluorescent	0.73
Incandescent	1.00
3000 K Fluorescent	1.08
6500 K Fluorescent	2.07
8000 K Fluorescent	2.11
7900 K Metal halide	2.22
17,000 K Fluorescent	3.84
Blue LED	17.60

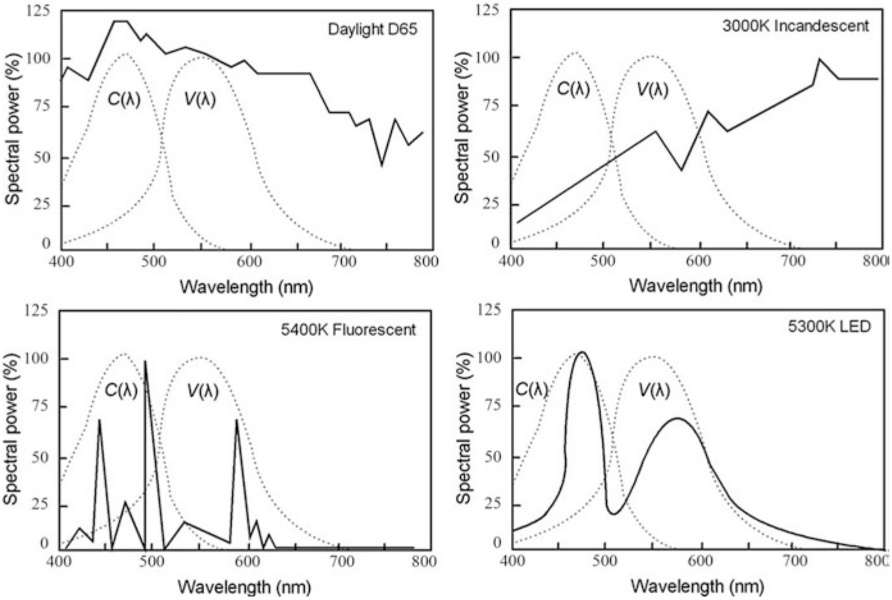
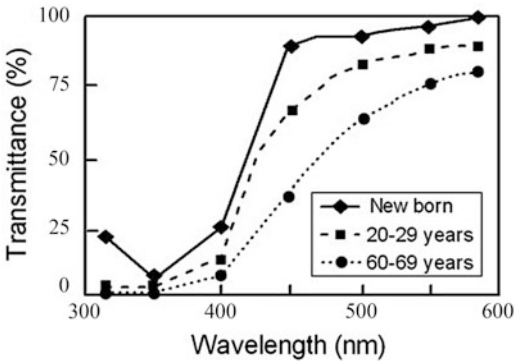


Fig. 8 The spectral powers of daylight, fluorescent, incandescent, and LED [18, 35, 36]

Fig. 9 Lens transmittances for various age categories [40]



field [39]. The illuminance at eyes is about two times of the horizontal illuminance on the working plane when people look towards the window, and is four to six times than that when people look at the working plane and the computer screen [38]. Thus, large window openings, the seat orientation toward windows, and the lounge space near windows are recommended for the room of long dwelling time. In addition, it is also an effective strategy that occupants look outside through windows by adaptive behaviors.

Besides, the lighting level of the nonvisual effect for the aged people is much higher, because the eye function has been degenerated. The lens transmittances for various age categories are shown in Fig. 9. It demonstrates that the transmittance of lens decreases as aging, especially for the shortwave range within 400–500 nm which has the greatest impact on the nonvisual effect. In addition, the aged people usually stay in the indoor environment for the worse mobility. Thus, adequate daylighting should be ensured, and outdoor activities are recommended for the aged people.

The Evaluation of the Nonvisual Effect of Existed Chinese Daylighting Design Standard

Daylighting can both satisfy the vision system and the nonvision system. To investigate the current situations of existed Chinese daylighting environments, the nonvisual effect of the different design level in Chinese daylighting standard (GB/T 50033-2013) [41] can be evaluated on basis of the preliminary empirical data of the nonvisual effect.

The Evaluation Method of the Nonvisual Effect

In daylighting design standard GB/T 50033-2013, the overcast sky condition is adopted in terms of the worst principle. It means that the dose-response function between the nonvisual effect and light under the overcast sky condition is needed. Besides, only the averages which are maintained at the horizontal illuminance on work plane are given for different design levels in the standard. Thus, there is a need of a convection method from the horizontal illuminance on work plane to the vertical illuminance at eyes.

Andersen et al. have proposed a simple ramp-function between the illuminance at eyes and the nonvisual effect under different daylighting conditions as shown in Fig. 10 [18]. The ramp function is established on empirical data from the nighttime study conducted by Cajochen et al. [30] and the daytime study conducted by Phipps-Nelson [32]. Two assumptions are proposed for this ramp-function. One is the illuminance threshold in the daytime to keep high alertness which is higher than that of the threshold during the night, because people are more sensitive to light at night; the other one is that if a significant effect is found during the daytime with a given illuminance, this effect will probably be observed with an even higher illuminance.

On the other hand, Kosir et al. have found the measured ratio between the vertical illuminance at eyes in the gaze direction towards the window and the horizontal illuminance on the work plane is relatively constant within a range of 1.8–2.1 during work hours, even though the external sky conditions are very variable [38]. The simulation results also confirm the stable ratio within a range of 1.5–2.0, although the ratio is lower than the measured one because of the simulation results generally lower than the measured data for conservative considerations. Thus, the ratio from 1.5 to 2.0 on the safe side is recommended for a rough convection method to calculate the vertical illuminance at eyes from the horizontal illuminance on the work plane.

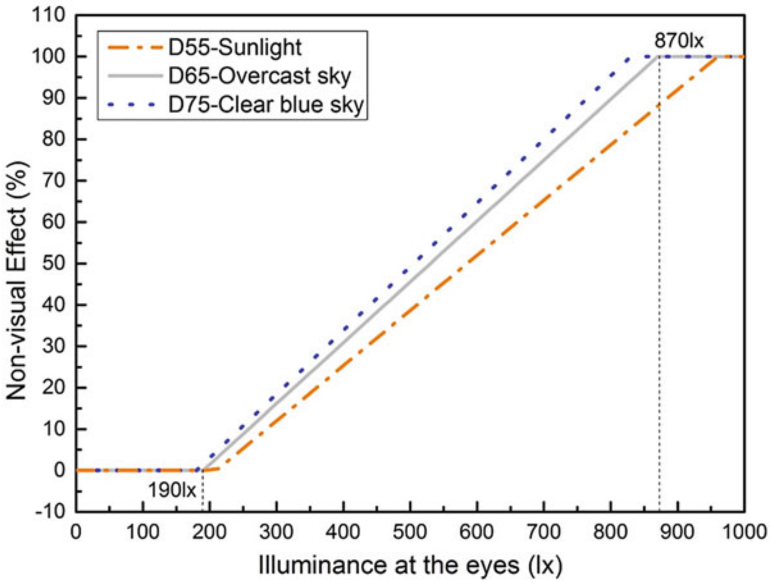


Fig. 10 The nonvisual effect under CIE D55, D65, and D75 [18]

The Nonvisual Effect of Different Design Levels

Among the five design levels in daylighting standard (GB/T 50033-2013), level I and level II are for the specific rooms which need high illuminance; level III is for the major rooms in public buildings; level IV is for the major rooms in residential buildings and the office rooms in hospital; level V is for the transition space and the toilets of buildings. The daylighting standard only offers the maintained horizontal illuminance within the range of 150 ~ 750 lx in the design levels from I to V. Therefore, it is demanded to find a conversion method to calculate the illuminance at eyes from the maintained horizontal illuminance. Kosir et al. have proposed a simple method to calculate the vertical illuminance by a constant ratio between the vertical illuminance and the horizontal illuminance [38]. Based on the simple method, the average illuminance at eyes at 1.2 m, higher than the floor, is calculated with the aid of the constant ratio. Then the nonvisual effect of different design levels can be given according to Fig. 10 in Table 3.

The evaluation results demonstrate that the nonvisual potential is satisfied for the design level of I or II and for level III at critical state, lower for level IV, and extremely low for level V. In addition, it reveals that the daylighting environments in office rooms where most people stay in the daytime have adequate illuminance at eyes to just satisfy the nonvisual effect, if the actual illuminance is higher under normal conditions than the design overcast sky condition based on the worst principle. However, if there is a consideration that the aged people who often stay at home and need higher illuminance with the degradation of the eye function [40], the daylighting level IV for the major rooms in buildings should be improved. Besides, although the daylighting level V for transition space is extremely low, the nonvisual effect may be ignored as the short dwell time.

Table 3 The percentages of the nonvisual effect of different design levels

Design level	Maintained horizontal illuminance lx	Illuminance at eyes[a,b] lx	Nonvisual effect %
I	750	1125 ~ 1500	100
II	600	900 ~ 1200	100
III	450	675 ~ 900	71 ~ 100
IV	300	450 ~ 600	38 ~ 60
V	150	225 ~ 300	5 ~ 16

[a]The illuminance at eyes is vertical at 1.2 m, higher than the floor, and is perpendicular to lighting windows
[b]The illuminance at eyes is calculated from the ratio between the vertical illuminance and the horizontal illuminance with the daily average value of 2.0 and the conservative value of 1.5

The evaluation method uses the maintained horizontal illuminance that is the average illuminance on the horizontal plane in the room, which means that the illuminance at eyes is the average vertical illuminance of indoor space. Therefore, the nonvisual evaluation results are only for a whole space and limited to represent space distribution. Besides, the illuminance at eyes varies greatly in different gaze directions, and its number depends on the proportion of the lighting windows in the field of view [39]. The vertical illuminance which is perpendicular to lighting windows is one of maximum illuminances achieved at eyes [38]. Thus, the evaluation result in Table 3 represents the maximum nonvisual potential of the space. If the different gaze directions of actual seat orientation are taken into consideration, much higher design illuminance that may be uneconomical will be needed for nonvisual stimulation. Therefore, if people make the adaptive behavior of gazing towards windows, the average vertical illuminance that is perpendicular to lighting windows is an appropriate index to evaluate the nonvisual potential of a whole space.

Field Validation

A field measurement has been conducted to valid the evaluation results of the nonvisual effect of level III, which is adopted for the major rooms in public buildings where most people stay during the daytime. The measurement selects an office room with the north-oriented unilateral daylighting in Dalian in typical daylight climate zone where the externally unobstructed and horizontal illuminance is 1500 lx.

Methods

The test room has two north-oriented lighting windows which are 1.0 m high from the floor. The size of the window is 2.1 square meter. In addition, the net height of the test room is 4.0 m, and the detailed floor plan is shown in Fig. 11.

Based on the dimension of the room and the windows, the ratio of glazing area to floor area in the test room is 1/5, and the depth of daylighting zone is 2.3. Obviously,

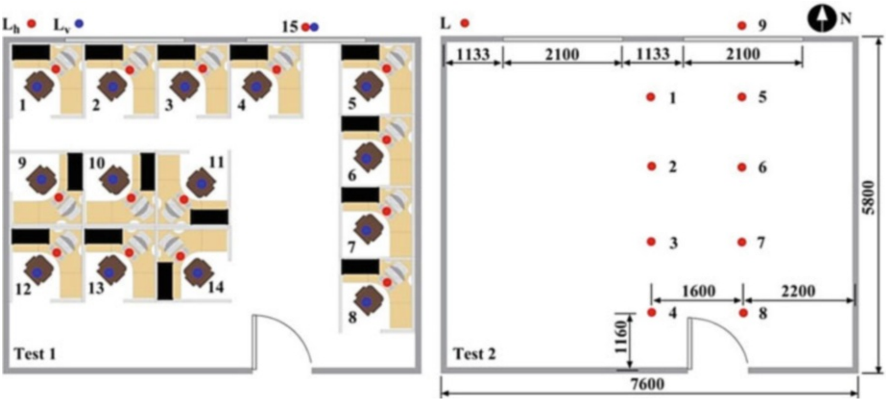


Fig. 11 The floor plan of the room and the locations of measuring points

Table 4 The daylighting design indexes of different levels [41]

Design level	The ratio of glazing area to floor area[a] A_w/A_f	The depth of daylighting zone[b] B/h_c
I	1/3	1.8
II	1/4	2.0
III	1/5	2.5
IV	1/6	3.0
V	1/10	4.0

[a] A_w/A_f, A_w is the glazing area of the windows, while A_f is the floor area
[b] B/h_c, B is the depth of the room, while h_c is the height from the working plane to the head of window

those design indexes conform to the recommended design indexes of design level III as shown in Table 4.

In the measurement, two sets of hourly tests were conducted during 08:00 ~ 17:00 from July 9th, 2005 to July 15th, 2005 as shown in Fig. 11. In test 1, the illuminance at every work station was measured by a hand-held light meter (Taiwan, Tes-1339, ±3%). Meanwhile, it also demonstrated the horizontal illuminance on the working plane (0.8 m high from floor), the vertical illuminance towards windows (1.2 m high from floor), the illuminance at eyes towards the working plane, and the illuminances at screens and windows (1.2 m high from floor) as shown in Fig. 12. On the other side, test 2 measured the unshaded vertical illuminance and the horizontal illuminance with the depth change of daylighting zone as shown in Fig. 11.

In test 1, hourly illuminances at eyes of four gaze directions were measured to choose a gaze direction which could represent the maximum nonvisual effect under working stations. In addition, the test 2 was conducted to investigate the ratio of the vertical illuminance to the horizontal illuminance and the nonvisual potential of indoor space without the shade of furniture.

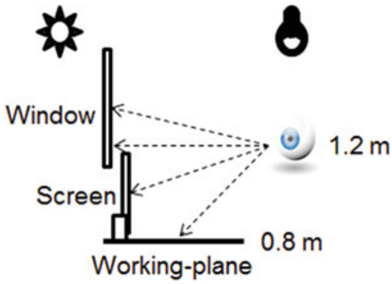


Fig. 12 The illuminances measured at eyes in different gaze directions

Table 5 The illuminances at eyes in different gaze directions

	Illuminance at eyes (lx)	
Gaze direction	Overcast day	Sunny day
Towards the windows	901	1530
Perpendicular to the windows (vertical illuminance)	813	1329
Towards the computer screen	354	525
Towards the working plane	510	778

The Effect of Different Gaze Directions on the Illuminance at Eyes

The daily average illuminances at eyes of four gaze directions are given in Table 5. It indicates that the illuminance towards windows is the highest with the highest sky proportion in the field of view, and the vertical illuminance is close to the highest one, while the others are much lower. However, the illuminance towards windows is not easily obtained through standardized measurement or calculation, because its measure angle always changes on different locations. Therefore, the vertical illuminance towards windows is an appropriate alternative to represent the maximum nonvisual potential, and is used as an index in nonvisual evaluation studies.

After the elimination of the shade influence of furniture, Fig. 13 shows the hourly ratios, measured in test 2, of the vertical illuminance to the horizontal illuminance in a sunny day and an overcast day. It reveals that the daily average ratio of the vertical illuminance to the horizontal illuminance at any time or measure point under various sky conditions is close to 2.0. In addition, all measured ratios are above 1.5, which supports the conservative assumption that the constant ratio is 1.5. Moreover, these results are also in accordance with the research by Kosir et al [38]. Therefore, the constant ratio assumption can be used to easily convert the average horizontal illuminance on the working plane to the vertical illuminance at eyes towards windows.

The Spatial Distribution of the Nonvisual Effect Towards Windows During the Day

Figure 14 shows that the hourly nonvisual effects on measured points can be calculated on basis of the measured vertical illuminances at eyes in test 1 and test

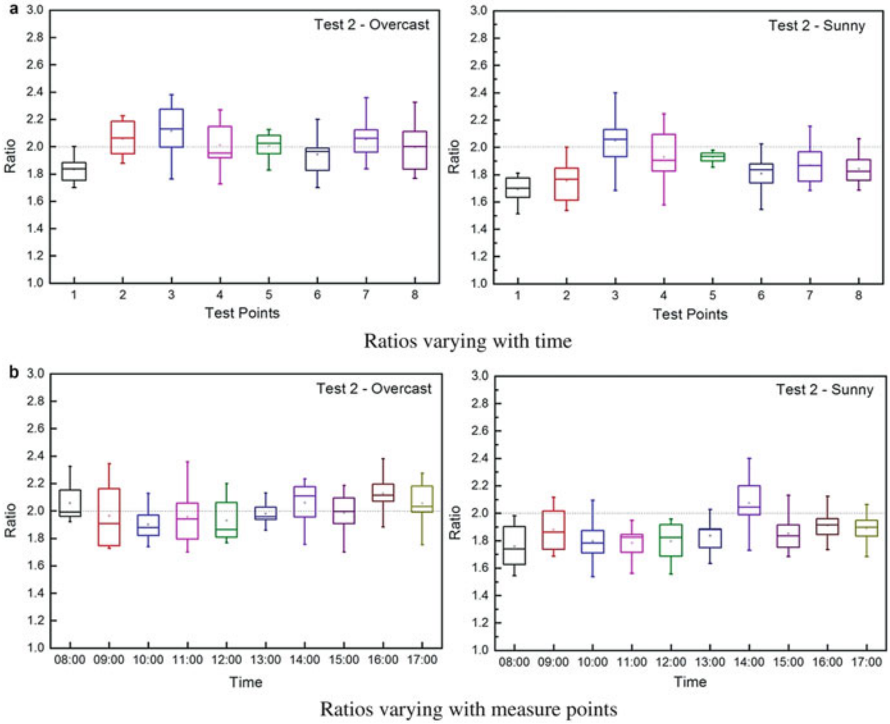


Fig. 13 The hourly measured ratios between the vertical illuminance and the horizontal illuminance

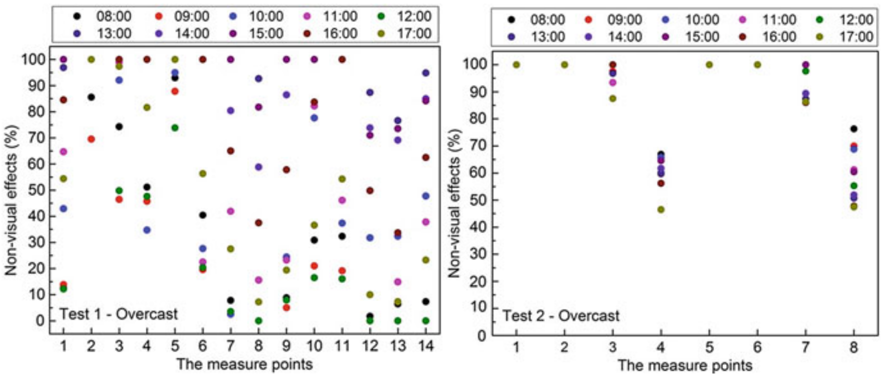


Fig. 14 The nonvisual effect towards windows on different measuring points in the overcast day

2 and the dose-response curve in Fig. 10. Obviously, the nonvisual effect decreases with the depth of the room. Without the shade of furniture, the nonvisual effects at the deepest measure points of 4 and 8 in test 2 are over 50%, while the others' are

over 80% in most hours of the overcast day. On the other side, the nonvisual effect in test 1 is significant but lower than that in test 2 due to the shade of furniture. In test 1, the nonvisual effects of measure points from 1 to 5 close to windows are at high level over half time of an overcast day; for the measure points from 6 to 11 in the middle of the room, their nonvisual effects can reach to 100% in few hours; for the measure points from 8 to 14, the nonvisual effects of the deepest row are still over 80% in few hours. The test results indicate that the occupants in the test room which adopt design level III may have adequate nonvisual effect stimulus, which is under the consideration that the illuminance is higher in normal conditions than that in the overcast sky.

The Average Nonvisual Effect Towards the Windows

In Table 3, the average nonvisual effects of different design levels in a room are calculated on basis of the maintained horizontal illuminance limited in GB/T 50033-2013. To validate evaluation results, this paper compares the illuminance at eyes obtained by the design empirical formula by Lynes or filed measurement.

Lynes's empirical formula (Eq. 1), provided in GB/T 50033-2013, is validated through simulation [42]. According to the test room dimension in Fig. 11, the designed average horizontal illuminance in the room is calculated by Lynes's formula as shown in Table 6. Then the average vertical illuminance in the room is calculated by the ratio of the vertical illuminance to the horizontal illuminance, and the nonvisual effect is given in terms of Fig. 10.

$$C_{av} = \frac{A_c \tau \theta}{A_z \left(1 - \rho_j^2\right)}, \quad (1)$$

where C_{av} is the average daylight factor of indoor surface, %; A_c points the area of window opening, m^2; τ represents the total transmittance of windows which is the product of glass transmittance, shade, and contamination reduction factors; θ means that the visible sky angle is 90° from the central point of the window, when there is

Table 6 The evaluation results of the nonvisual effect through different methods for design level III

Method	I_{hor} [a](lx)	I_{ver} [b](lx)	α[c]	Nonvisual effect
Standard limit	450	675 ~ 900[d]	1.50 ~ 2.00	71% ~ 100%
Design formula	549	823 ~ 1098[d]	1.50 ~ 2.00	93% ~ 100%
Field measurement	596	1179[d]	1.98	100%

[a]I_{hor} is the horizontal illuminance; [b]I_{ver} is the vertical illuminance; [c]α is the ratio of the vertical illuminance and the horizontal illuminance

[d]Three methods are used to obtain the vertical illuminance (illuminance at eyes). The first one is based on standard limit values and the constant value of α. The second one is firstly used to calculate the horizontal illuminance according to Lynes's empirical formula, and then based on the constant value of α. The last one is to measure the horizontal illuminance and the vertical illuminance in field test 2

no outdoor shelter; A_z implies the total area of indoor surface, m^2; ρ_j is weighted average reflectivity of indoor surface.

On the other side, Table 6 shows the measured averages of the horizontal illuminance and the vertical illuminance of the room in test 2 under overcast sky condition and the actual average nonvisual effect. The actual ratio of the average horizontal illuminance and the average vertical illuminance is 1.98 which is close to the constant ratio assumption of 2.0.

In Table 6, it demonstrates that the nonvisual effect calculated on basis of the standard limit or Lynes's formula is close to the field measurement results. Notwithstanding, the design calculation methods are conservative, especially for the design indexes of the window dimension in Table 4 which are recommended in GB/T 50033-2013.

Conclusion

Since the industrial revolution, most people have been spending their daytime in indoor environments instead of outdoor environments. There is about 40–200 times of light exposure for the people who work in outdoor or very close to windows [9]. Except for visual effect, recent discoveries in photobiology indicate that the nonvisual effect of light has significant influences on well-being, health, mood, and productivity. Besides, the nonvisual effect regulates the production of many hormones, which means that light may have impacts on many aspects of human physiology. However, the vision system is the base of conversation photometry and lighting design standards. In addition, considering the health risk of radiation and the comfort of the visual system, the standard limits have been minimized, while there are many differences for the demands of the nonvisual effect.

Preliminary recommendations of single exposure factor of the nonvisual effect may be given from some empirical findings, though the complex dynamic light exposure of the nonvisual physiology is far from completion considering the interactions among spectrum, intensity, timing, duration, and history.

The spectral luminous efficiency curve $C(\lambda)$ of the nonvisual effect is different from $V(\lambda)$ of the visual system, because the nonvisual photoreceptors are sensitive to blue-green light with the peak at 450 nm and the visual photoreceptors are sensitive to yellow-red light with the peak at 555 nm. Although different spectral sensitivity functions of $C(\lambda)$ have been reported, the percentage deviations of the circadian efficiency or the circadian faction factor calculated with different values of $C(\lambda)$ will not exceed 4% [25]. Thus, the preliminary nonvisual photometry can be established.

Besides, it reaches an agreement about the exposure timing which is that people need bright light exposure during daytime for better alertness, good mood, and higher productivity and dim light exposure at night to not disrupt the circadian rhythm. In addition, the intensity thresholds of light exposure at different times can be given on basis of lots of empirical data. The upper limit of light exposure to keep body at high-level alertness may be over 1000 lx in the daytime, while the lower limit to not disrupt the circadian rhythm may be lower than 50 lx or even 15 lx due to the higher light sensitivity at night. Notwithstanding, the therapy threshold of light exposure for people who suffer from seasonal affected disorder and Alzheimer's syndrome may be over 2000 lx during certain hours in the daytime.

On the other side, some experiments have reported that the short duration of bright light exposure at the start has the greatest effect. However, the nonlinear duration response of the circadian system needs further investigation to be determined by different light intensities, spectra, and times in a day.

Based on the before-mentioned photobiology between light exposure and the nonvisual effect, the preliminary evaluation methods of the nonvisual effect can be established. Besides, it may be the main impact of a greater understanding of the role of light exposure in human well-being and will return attention to the better daylighting of buildings, both of which are well suited for the vision system and the nonvision system.

Therefore, the nonvisual effects of different design levels in Chinese daylighting standard GB/T 50033-2013 are evaluated to explore the current situations of the daylighting environments in existed buildings. The evaluated nonvisual effect of the ratings from I to V is respectively 100%, 100%, 71–100%, 38–60%, and 5–16%. The results demonstrate that the nonvisual potential is satisfied for the design level of I or II and for level III at critical state, lower for level IV, and extremely low for level V. It reveals that the daylighting environments in office rooms where most people stay in the daytime have adequate illuminance at eyes for the nonvisual effect, if the actual illuminance is usually higher under normal conditions than that under overcast sky conditions. However, with the consideration that the aged people who often stay at home and need higher illuminance with the degradation of the eye function [40], the daylighting level of IV for the major rooms in residential buildings should be improved. Besides, although the daylighting level of V for transition space is extremely low, the nonvisual effect may be ignored as short dwell time.

During the process of evaluation, the ratio of the horizontal illuminance on the work plane to the vertical illuminance at eyes ranging from 1.5–2.0 is used to convert the maintained horizontal illuminance to the room average vertical illuminance. It is conservative when the ratio is 1.5 and in an average state when the ratio is 2.0. Then the nonvisual effect is calculated on basis of the room average vertical illuminance according to the ramp-function model. Thus, the evaluation results of different design levels only represent the room average state in gaze direction towards windows.

A field measurement is conducted to validate the nonvisual effect evaluation results of design level III, which is adopted for the major rooms in public buildings where most people stay in the daytime. The nonvisual effect evaluated with the aid of the measured data in an overcast day is much close to that of the evaluation result based on the maintained horizontal illuminance in GB/T 50033-2013. On the other side, the nonvisual effect evaluated based on Lynes's formula and the design indexes of the room dimension in Table 2 which is recommended in the standard are also in accordance with the evaluation result based on the maintained horizontal illuminance.

Besides, the measured illuminances at eyes in different gaze directions indicate that the illuminance towards the window is the highest with the highest sky proportion in the field of view. Meanwhile, the vertical illuminance is close to the highest one, while the others are much lower. However, the illuminance towards the window is not easily obtained by standardized measurement or calculation with the angle always varying with different locations. Therefore, the vertical illuminance is an appropriate alternative to represent the maximum nonvisual potential. In addition, the hourly ratios of the horizontal illuminance on the work plane (0.8 m) to the vertical illuminance at eyes (1.2 m) towards the window on different measure points in test 1 and test 2 are calculated. It reveals that the daily average ratio of the vertical illuminance to the horizontal illuminance at any time or measure point under various sky conditions is close to 2.0. What is more, all measured ratios are above 1.5, which supports the conservative assumption that the constant ratio is 1.5.

Although the nonvisual effect of the daylighting environment can be preliminarily evaluated, more valid findings on how the dynamic light exposure impacts the nonvisual physiology are needed in the future. New findings will refine the evaluation methods at present and lead to the regulation in future lighting standards.

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