Influence of the spectrum of all-day LED lighting on human daytime and nighttime performance

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Abstract

Indoor LED lighting is directly related to people's health and performance. This experiment investigated the effect of the spectrum of LED lighting on human daytime and nighttime performance. Six different LEDs were selected for the experiment: ordinary LEDs and daylight LEDs that mimic the full spectrum, with CCTs of 2700K, 4000K, and 5000K for each spectral type (2 spectral types * 3 CCT). A total of 24 subjects participated in the experiment. Each subject was assigned to a specific CCT and experienced two spectral types on different days. Subjects were given a predetermined light exposure for 12 hours a day for each experiment. By analyzing the subjects' performance during the daytime light exposure and nighttime sleep quality after, we found that daytime exposure to light with stronger non-visual stimulus led to higher daytime alertness and better nighttime sleep quality, and the lack of daytime light stimuli led to poor night sleep quality. However, changes in spectral composition within a small range were not enough to cause a sufficiently significantly improve in daily human performance.

Introduction

Light is an important factor in stabilizing the human circadian rhythm. In modern society, people spend more and more time indoors, represented by the office. Artificial lighting profoundly impacts people's lives, so indoor LED lighting is directly related to people's health and performance [1, 2]. The spectral composition of LED lighting has strong plasticity, and different types of LED lighting have different effects on human physiological indicators. Compared with ordinary LED, the spectrum of full-spectrum LED is more similar to that of sunlight. A previous study showed better color rendering and effect [3]. Therefore, full-spectrum LED is expected to be used in more scenes to improve people's performance, feelings, and health.

Non-visual channel dominated by ipRGC affects the human body's performance, sleep quality, hormone secretion, etc. Non-visual effects are also significantly affected by spectral components. For example, the inhibition of melatonin is closely related to cortisol secretion and spectral composition [4]. Previous studies have shown that exposure to light rich in blue light before sleep can make people more alert and worse asleep [5]. The research of Hou et al. also shows that the alertness, brain activity and sleep caused by exposure to light with the same CCT and different spectral components are different [6]. Some studies have created indicators to describe the effects of spectral components on non-visual effects. For example, Rea et al. have established CS values since 2012 to describe the level of the non-visual stimulus of light based on melatonin inhibition caused by light stimulation to predict the response of the rhythmic system to external light [7,8]. CIE recommends using EDI to describe the response of ipRGCs to light [9]. Brown et al. pointed out that melatonin inhibition, subjective alertness, and rhythmic phase migration positively correlate with melanopic EDI [10, 11]. In the study, LED lamps of different CCT and spectrum types were compared to explore the use of LED in the office. At the same time, spectral components and their non-visual stimulus levels were considered to explore the impact of daylight LED on daytime alertness and nighttime sleep.

Method

The experiment was conducted in an office-simulated room with matt white or grey walls, ceilings, curtains, and furniture (Figure 1). No outside light entered the room. Ten tables and chairs were placed in the room, with partitions between each table to prevent interruption. The lamps were all mounted on the ceiling, with six adjustable flat lamps providing pre-defined light for the experiment and two fluorescent lamps on the ceiling (Philips, 3000K) providing basic light.

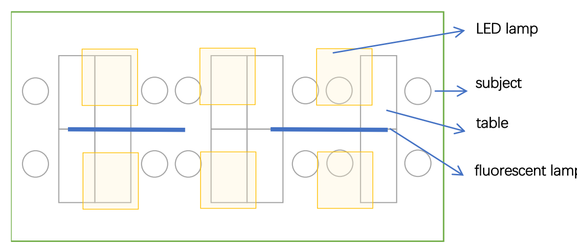

Figure 1 Experimental setting

In this experiment, two spectral types, normal LED and daylight LED with simulated full spectrum, were selected, and three kinds of 2700K, 4000K and 5000K CCT were selected for each spectral type, forming a total of six experimental conditions (Figure 2, NL=normal LEDs, DL=daylight LEDs). Eye position illuminance was controlled to 500lx under each condition and was measured at 10 locations to ensure uniformity. To explore the effects of nonvisual systems, melanopic EDI values were calculated using CIE S 026 Toolbox and CS (circadian stimulus) values were calculated according to CS2.0 using Circadian Stimulus Calculator developed ed by Rea et al. for each condition (Table 1). In addition, the fluorescent lamp provided basic illumination with an eye level of 80lx for use during preparation and rest periods which has almost no non-visual impact on human.

A total of 24 subjects participated in the experiment, and each subject was assigned to a specific CCT group (Group A for 5000K of 9 subjects, Group B for 4000K of 8 subjects, and Group C for 2700K of 7 subjects). 4 males and 5 females (age=21.4±2.07) were included in Group A, 3 males and 5 females (age=23.5±1.60) were included in Group B, and 1

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male and 4 females (age=23.0±3.27) were included in Group C. All subjects were of an intermediate type and had no sleep disturbances for a month. Each subject came to the laboratory on different days to experience two spectral types. The same subject received a one-week washout period between each exposure to avoid the effect of the last light. Subjects were asked to maintain a regular routine and report their sleep every day throughout the whole experiment.

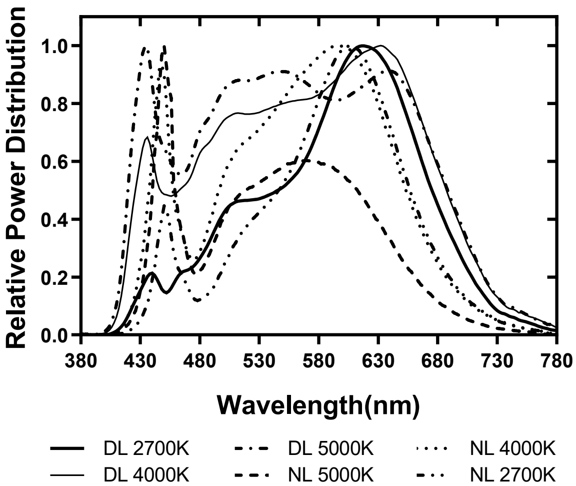

Figure 2 SPDs of 6 experimental conditions

Each subject followed the process shown in Figure 3 every time they came to the laboratory. They were asked to arrive at the laboratory at 8:30 in the morning every day and then have half an hour of dark adaptation to avoid the influence of external light. From 9 o'clock, subjects were required to do paperwork under preset light of different conditions. At 17:00, the preset lighting was turned off, and the subjects stayed at 21:00 under the basic lighting provided by the fluorescent lamp, then left the laboratory and went home to sleep. The Stanford Sleep Scale (SSS) was tested every hour to assess daytime alertness during the laboratory. The next morning, the subjects were asked to complete an online questionnaire after woke up, including the Groningen Sleep Quality Scale (GSQS) and the Consensus Sleep Diary (CSD), to assess sleep quality at night. During laboratory illumination, the subjects are not allowed to use electronic equipment to prevent additional light stimulation. In this study, one-way ANOVA was used to test the mean difference between groups, and all statistical analyses were performed by SPSS 20.0.

Table 1 Information of light conditions and basic lighting

CCT (K)	Type	Ev @ eye position (lx)	Melanopic EDI (lx)	CS value
2700	NL	500	197.43	0.355
	DL		243.63	0.369
4000	NL		296.80	0.372
	DL		362.99	0.411
5000	NL		369.55	0.424
	DL		403.42	0.436
3000	Fluorescent	80	25.24	0.066

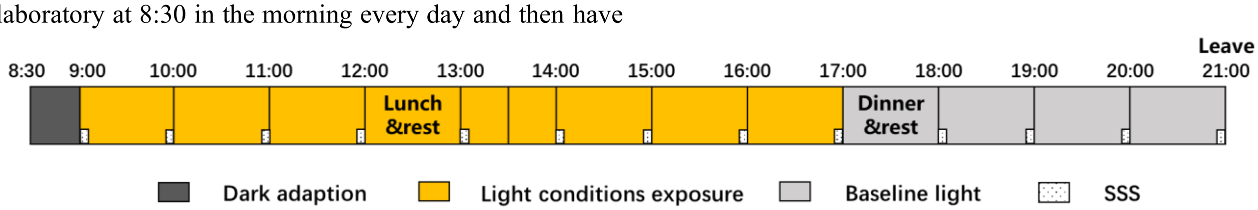

Figure 3 Experimental procedure

Data analysis

Daytime alertness

The average value of Time 1 toTime10 during the daytime of SSS each day is calculated as the all-day alertness score of the whole day. The higher score indicates lower alertness. The results of ANOVA of CCT and spectral types showed that both had no significant impact on the alertness of the whole day. Specific data are shown in Table 2.

Table 2 the mean and SD values of all-day alertness in each condition

CCT	Type	Mean	SD
2700K	NL	3.365	0.7770
	DL	3.389	0.8337
4000K	NL	3.262	0.5583
	DL	2.691	1.1821
5000K	NL	3.090	0.9655
	DL	3.100	0.9636

One-way ANOVA shows there was no significant difference under each light condition. Figure 4 shows the relationship between the average melanopic EDI of each light condition and the all-day alertness with the trend line of the linear fitting. The results showed that the high non-visual stimulus light in the daytime tended to increase the overall alertness level throughout the day.

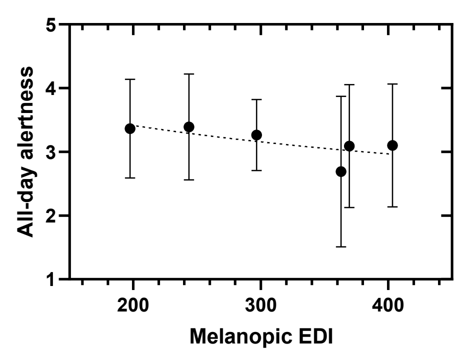

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Figure 4 the result of all-day alertness in each condition with melanopic EDI (p>0.05). The dotted line represents the changing trend fitted by the dose-response curve.

Sleep quality

Scores of the Groningen sleep quality scale (GSQS) and consensus sleep diary (CSD) were recorded to assess sleep quality. The total score on the GSQS is a result of the summation of the scores from the two questions 'how did you sleep last night?' CSD, as a 'Sleep Quality Score', ranging from 0-19, with higher scores representing worse sleep quality.

Two-way ANOVA on CCT and spectral type revealed a significant effect of CCT on the Sleep Quality Score (F = 4.810, P = 0.014). In addition, post hoc tests showed that sleep quality scores at 4000K were significantly lower than at 2700k (P = 0.014), indicating that sleep quality at 4000K was significantly better than at 2700k (Figure 5). However, the spectral type had no significant effect on the Sleep Quality Score.

One-way ANOVA on the Sleep Quality Score for each light condition revealed a significant effect on sleep quality (F = 2.600, P = 0.041). Figure 6 shows the relationship between melanopic EDI and the Sleep Quality Scores for each light condition and plots the trend line of the quadratic function fit. The results showed that too low daytime non-visual stimulation tended to decrease the nighttime sleep quality.

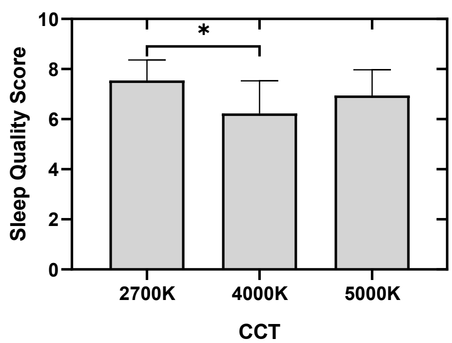

Figure 5 the result of Sleep Quality Score in 3 CCTs (*p<0.05)

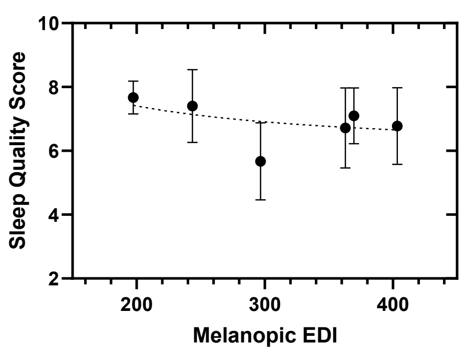

Figure 6 the result of the Sleep Quality Score in each condition with melanopic EDI (p>0.05). The dotted line represents the changing trend fitted by the dose-response curve.

Discussion

This study explored the influence of CCT and spectrum type of LED on human day and night performance. For LED lamps, CCT and type affect their spectral composition. In terms of spectral components, full-spectrum LED is characterized by more blue light components in its spectrum than ordinary LED, so it has a higher level of non-visual stimulation. For the human physiological system, the non-visual channel of light mainly affects daytime alertness and night sleep. Therefore, this study believes that the difference in non-visual stimulus levels between various lighting conditions is the fundamental reason for the difference in human performance. The six light conditions set in this experiment showed different levels of rhythmic stimulus. Each light condition was characterized by melanopic EDI, which was considered to represent the response of the non-visual system. In this study, all-day alertness increased with the increase of non-visual stimulus levels, which is consistent with the conclusions of many previous studies [6, 12]. This study also indicates that night sleep quality was affected by daytime light. The low level of daytime non-visual stimulus led to poor sleep quality, which is consistent with previous studies report that the lack of daylight will lead to the decline of nighttime sleep quality and the high level of non-visual stimulation will lead to good sleep quality [6, 13].

In this study, CS and Melanopic EDI were proved to be able to predict the change trend of daytime alertness and night sleep quality. However, this study lacks significant conclusions. The reason for this is that the non-visual stimulus level of the lighting conditions selected for the office application scene in this study is similar. Melanopic EDI and CS of light conditions in this experiment are reported in Table 1. Since CS value itself ranges from 0 to 0.7, which directly represents the percentage of melatonin secretion caused by light, the CS range of 0.35 to 0.43 in this study can almost directly indicate that non-visual stimuli caused by each light are comparable without significant difference. Figueiro et al.'s research in the office also proves that there is no significant difference in the alertness under the light of CS with no significant difference, while CS with significant difference brings significant difference in alertness under the light [12]. In addition, the malenopic EDI in this study is about 200lx-400lx. Although EDI cannot directly reflect the degree of impact, Brown et al. provided evidence for their responsiveness. They reported the relationship between melanopic EDI and several physiological parameters, including subjective alertness [10-11]. The *lgEDI* range in this experiment is about 2.3-2.6, close to the response saturation zone of the curve reported by Brown, and is also too small to produce significant difference. In conclusion, in the future, the range of daytime light parameters should be increased to further explore the response of nighttime sleep quality to daytime light. In addition, the subjects in this study only received a specific day of light stimulation, which has limited impact on night sleep. The results of several months of field experiments show that long hours of office lighting can produce more significant effects.

The disadvantage of this study is that the lighting conditions were selected within the use range of daily office lighting, so there was no condition of too high or too low melanopic EDI, which limited the parameter range. In addition, the inter-group design may introduce more individual differences. Future research should increase the range of light stimulation, prolong the time of light stimulation, increase the number of subjects,

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and use more sensitive measurement methods for more in-depth research.

Conclusions

This study revealed the influence of spectral composition on night sleep and daytime alertness by exploring the influence of CCT and spectral type of office lighting LED on daily human performance. The experimental results show that daytime exposure to light with stronger non-visual stimuli will lead to higher daytime alertness and better sleep quality. Conversely, the lack of daytime light stimuli will lead to poor night sleep quality. However, changes in spectral composition within a small range and light exposure lasting only one day are not enough to cause sufficiently significant differences in day and night performance. This study suggests that different spectral types of LEDs, such as full spectrum LEDs with higher non-visual stimulation levels, should be rationally used in the office to improve people's work performance, rhythm, and sleep health in the future.

Acknowledgments

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