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Optimal Lighting Conditions for Office Workers from the Perspective of Non-visual Effects

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Abstract

Optimal lighting conditions for office environments were examined with respect to effects on productivity, alertness, subjective responses, sleep composition, and circadian rhythms of melatonin and body temperature. Participants were 10 healthy male students (mean age: 24.1 ± 1.1). Three lighting conditions were employed: (1) 750 lx and 5000 K, kept constant from 9:00 to 18:00 (JIS mode); (2) 400 lx and 5000 K, kept constant from 9:00 to 18:00 (SE mode); and (3) 750 lx and 6000 K from 9:00 to 14:00, followed by the eco circadian light control program (ECLCP), in which light intensity and correlated color temperature were gradually lowered to 400 lx and 4000 K from 14:00 to 17:00 and then kept constant until 18:00. Participants stayed in the chamber for approximately 48 h. They performed simulated office tasks from 9:00 to 17:30 with the exception of short breaks for rest and lunch. Simulated office work comprised two parts: (1) performance of the contingent negative variation (CNV) paradigm, and (2) performance of the Cognitive Performance Test of Productivity (CPTOP). Four sequential measurements in each set were employed: (1) subjective evaluation of the environment on a rating scale (3 min), (2) CNV paradigm (15 min), (3) CPTOP (30 min), and (4) rest (15 min). Two sets were carried out in the morning and three sets in the afternoon. Participants were exposed to dim light from 19:30 to 25:00, and saliva samples were taken every 30 min from 20:00 to 25:00 to analyze melatonin concentration. Participants went to bed at 25:30 (< 3 lx) and got up at 7:30. Rectal temperature was recorded during sleep from 25:30 to 7:30. Sleep architecture was also evaluated during this time period on the second night. The experimental conditions on the second day were identical to those on the first day. Data obtained on the second day were used for analysis. Average CNV amplitude in SE mode (400 lx) was significantly smaller than that in JIS mode (750 lx) and ECLCP. The number of errors in the selective response in the CNV paradigm under SE mode was significantly greater than that under JIS mode and ECLCP. The increases and decreases in rectal temperature between bedtime, nadir, and waking time were smallest in SE mode, while the increase was greatest in ECLCP. ECLCP conditions significantly advanced the phase of circadian rhythm and were associated with greater increases in melatonin compared with the JIS and SE conditions before bedtime. Polysomnograms during the first half of sleep tended to show a lower score of stage 3 sleep in SE mode compared with JIS mode and ECLCP, but did not reach the level of significance ($p < 0.1$).

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Results indicate that light intensities of less than 400 lx might affect not only alertness and productivity, but also the amplitude and phase of circadian rhythms including sleep composition. Light control conditions such as ECLCP appear to maintain appropriate circadian rhythms while retaining the work efficiency of the JIS mode.

Keywords: optimal light, office, circadian rhythms, melatonin, alertness, productivity

1. Introduction

Humans have created many artificial environments for daily living. However, it is important to understand human characteristics to achieve an optimal arrangement often referred to as 'good design'. Physiological anthropology is an approach to understanding humans from the viewpoint of adaptability to the environment, because all life forms on Earth must adapt to their habitats to survive [1]. We, *Homo sapiens*, have spent at least 95 percent of our species' existence as hunter-gatherers and have biologically adapted to survive in such an environment. Accordingly, humans do not necessarily possess the adaptability to cope with the sudden emergence of modern environments with a heavy emphasis on technology. There is a surely a conflict between the natural environment to which we have adapted and the artificial environment that we have created for ourselves for the sake of comfort and convenience. This conflict likely manifests as slight physiological tension and invisible stress. Here, we focus on adaptability to modern environments containing artificial lighting.

The activity of most organism is synchronized with natural light cycles or with changes in light intensity and spectral composition. Consequently, they have evolved circadian rhythms to fit their activities during day and night. The circadian rhythms of humans are also affected by changes in the lighting environment, but the intensity and spectral composition of the light in ordinary offices is constant. A case worth considering is the Great East Japan Earthquake of March 2011, which brought about an energy crisis. In most offices, the illuminance level was reduced to 400 lx or below, even though the Japan Industry Standard (JIS) recommends 750 lx for general office lighting conditions. It is likely that such lighting conditions with consistently low illuminance from morning to evening not only affected productivity and comfort in the office, but also disrupted circadian rhythms. The purpose of the study was to propose the appropriate conditions for office lighting by evaluating productivity, alertness, subjective responses, sleep composition, and circadian rhythms of melatonin and body temperature, and to call attention to non-visual effects of lighting in a simulated office.

2. Methods

2.1. Subjects

Ten healthy male students (mean age: 24.1 ± 1.1) participated in the study after completing a psychological interview and screening for sleep disorders, medication use, recent night work, and recent overseas travel across time zones. This study was approved by the Ethical Committee of the Faculty of Design, Kyushu University. Informed, written informed consent was obtained from all participants prior to enrollment. Participants were required to keep a regular 8-h sleep schedule for at least 5 days before the experiment, which was confirmed from their daily sleep diary and actigraph data (Actiwatch-L; Mini-Mitter Co. Inc.; Bend, OR). Participants were also asked to refrain from using caffeine, nicotine, and alcohol for one day before the experiment.

2.2. Experimental protocol

Each participant was exposed to the following three lighting conditions, which were separated by at least 5 days: 1) 750 lx and 5000 K, in accordance with Japan Industry Standard (JIS) recommendations, kept constant from 9:00 to 18:00 (JIS mode); 2) 400 lx and 5000 K, an energy-saving condition imposed following the Great East Japan Earthquake in 2011, was kept constant from 9:00 to 18:00 (SE mode); 3) 750 lx and 6000 K from 9:00 to 14:00, followed by a gradual decrease in intensity and correlated color temperature to 400 lx and 4000 K from 14:00 to 17:00, which were then held constant until 18:00, which is referred to as the eco circadian light control program (ECLCP). Across all lighting conditions, 400 lx and 5000 K was employed during lunch time from 12:00 to 13:00. A climate-controlled chamber was used for the experiment, in which the ambient temperature was kept at 25 ∘C with relative humidity of 50 percent.

Each participant stayed in the chamber for approximately 48 h. On the first day, the participant performed simulated office work from 9:00 to 17:30 with the exception of short breaks for rest and lunch time, and took a shower after 18:00 and ate the evening meal at approximately 18:30. These activities were performed under lighting conditions of 200 lx and 5000 K, which were in effect from 18:00 to 19:30. Next, the participant was exposed to dim light (i.e., less than 10 lx) from 19:30 to 25:00, while saliva samples were taken every 30 min from 20:00 to 25:00 to analyze melatonin concentration. The participant went to bed at 25:30 (light intensity of less than 3 lx), and got up at 7:30. Rectal temperature (LT-ST08-11, Gram) was recorded at 1-min intervals from 25:30 to 7:30. The experimental conditions on the second day were identical to those on the first day. Data obtained on the second day were used for analysis.

2.3. Tasks

Simulated office work was divided into two parts: 1) performance of the contingent negative variation (CNV) paradigm, and 2) performance of the Cognitive Performance Test of Productivity (CPTOP) task. CPTOP involved sorting slips according to the date, addressee, and financial sum displayed on an iPad [2].

2.4. Measurement

Four sequential measurements in each set were employed: 1) a rating scale applied to an eight-item subjective evaluation of the environment (bright–dark, comfort–discomfort, like–dislike, alertness, concentration, efficiency to complete work, ease of reading print on paper, and ease of reading print on a display) (3 min); 2) CNV paradigm (15 min); 3) CPTOP (30 min); and 4) rest (15 min). Two sets were carried out in the morning, and three sets in the afternoon.

CNV is one of the event-related potentials in the brain and was proposed by Walter et al. [3]. Electroencephalography (EEG) and electrooculography (EOG) were measured via Ag–AgCl disc electrodes located at Cz and Fz, according to the international 10–20 system with a linked ear reference (Polimate AP1000; TEIAC Co. Ltd.). In this study, cortical arousal level was evaluated by measuring the early component of CNV amplitude, averaged from 500 and 1000 ms after the warning signal (S1). Selective response time was obtained by using two signals (red and blue) as the imperative stimulus (S2). The participant was requested to push the button as soon as possible upon observing a red signal. The CNV paradigm was repeated 90 times over 15 min, during which the red signal appeared 62 times. The average response time and number of errors were considered measures of work performance.

In the CPTOP task, the number of sorted slips and the average sorting rate during 30 min were used as means of evaluating work performance.

Sleep architecture was also evaluated by scalp EEG (C3, C4, O1, O2, Fz, Cz) during the second night from 1:30 to 7:30. Electromyography (EMG) was added to EEG and EOG, and polysomnograms (PSG) were scored in 1-min epochs according to international criteria [4].

Saliva samples taken with a Salivette (Salivette; Sarstedt, Germany) were centrifuged and then frozen at −30 ∘C until assay. Melatonin levels of the samples were analyzed in duplicate with a commercially available ELISA kit (Direct Saliva Melatonin ELISA; BÜHLMANN Laboratories; Schönenbuch, Switzerland), and mean values of the duplicate were employed for elucidation.

2.5. Data analysis

The means of CNV amplitude, number of errors, increases and decreases in rectal temperatures, DLMO, and number of epochs of stage 3 sleep were compared across lighting conditions using a two-tailed paired *t*-test. Temporal changes in CNV amplitude and rectal temperature were analyzed by two-way analysis of variance.

Statistical analyses were performed using SPSS version 16.0 (SPSS, Chicago, IL). Differences for which p was < 0.05 were considered statistically significant.

3. Results

The averages of the early component of CNV amplitude for five sets of the CNV paradigm were compared across the three lighting conditions because there was no significant difference in time factor according to analysis of variance. Average CNV amplitude, obtained from both Fz and Cz, was significantly smaller in SE mode (400 lx) compared with JIS mode (750 lx) and ECLCP (Figure 1). The number of errors in the selective response was significantly greater in SE mode compared with JIS mode and ECLCP (Figure 2), although selective response time was the same across all three lighting conditions. There were no differences in CNV amplitude or number of errors between JIS mode and ECLCP. On the other hand, results of CPTOP showed no difference in the number of sorted slips or average sorting rate across lighting conditions. However, a post-lunch dips in both CPTOP performance in SE mode and CNV amplitude in JIS mode were observed during the first set of the afternoon.

Figure 3a shows temporal change in rectal temperature during sleep, which indicates the effects of daytime lighting conditions on core body temperature rhythm at night. When comparing rectal temperature at bedtime (25:30) to the nadir, the decrease was significantly smaller in SE mode compared with JIS mode and ECLCP (Figure 3b). The increase in rectal temperature from the nadir to the wake-up time was smallest in SE mode, and largest in ECLCP (Figure 3c).

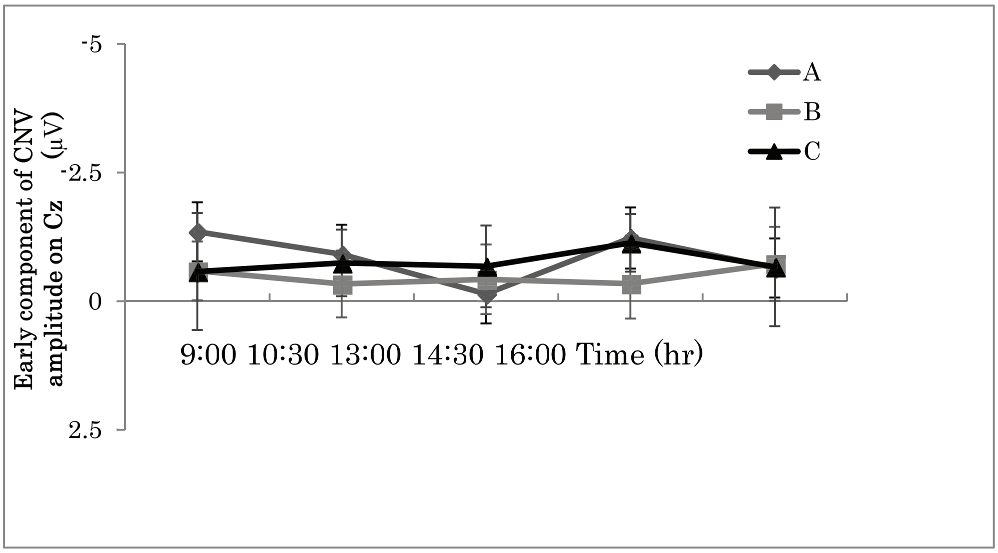


Figure 1: Average amplitude of CNV in a daytime (M ± S.D.). A: Japan Industry Standard (JIS) mode; 750 lux with 5000K, constant; B: Saving Energy (SE) mode; 400 lux with 5000K, constant; C: Eco Circadian Light Control Program (ECLCP); 750 lux with 6000K until 14:00 followed by being lowered to 400 lux with 4000K until 17:00.

As shown in Figure 4, daytime lighting conditions affected phase shift of the circadian rhythm of melatonin, as measured by dim light melatonin onset (DLMO) at night.

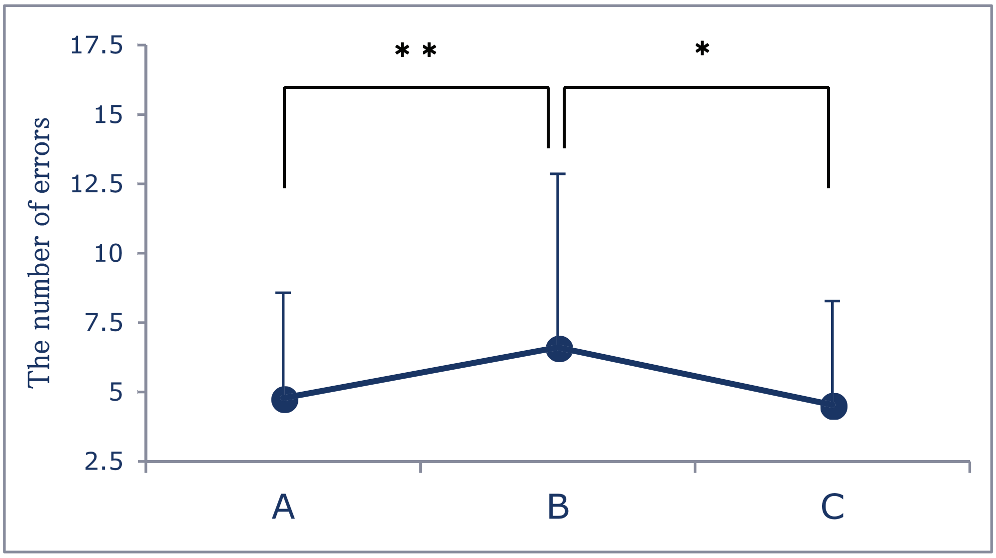
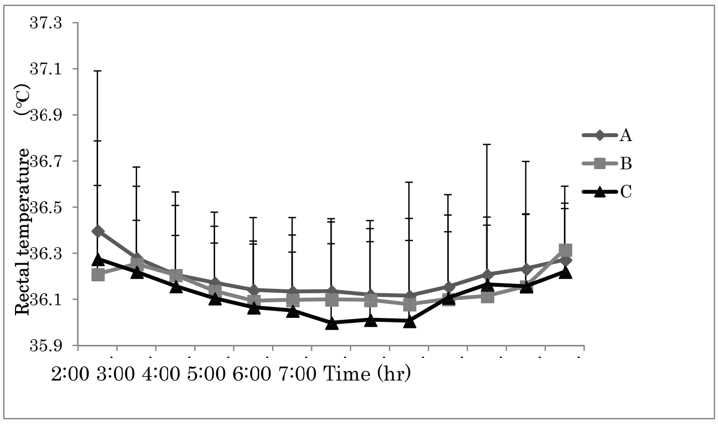
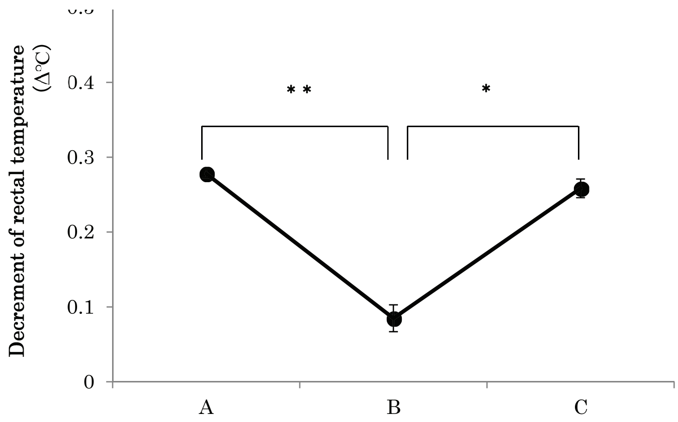


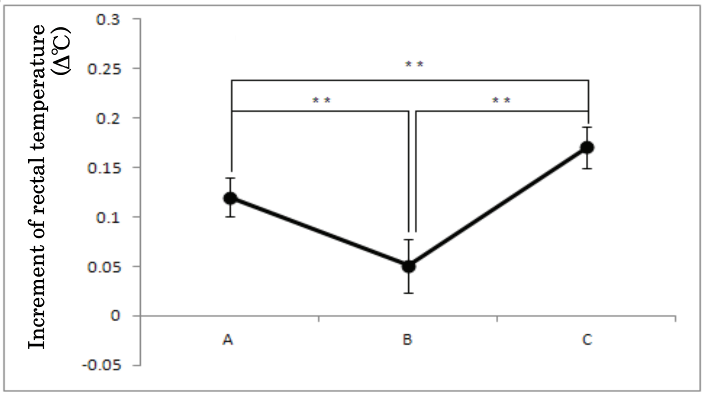
Figure 2: Number of errors obtained in the CNV paradigm (M+S.D.). A: Japan Industry Standard (JIS) mode; 750 lux with 5000K, constant; B: Saving Energy (SE) mode; 400 lux with 5000K, constant; C: Eco Circadian Light Control Program (ECLCP); 750 lux with 6000K until 14:00 followed by being lowered to 400 lux with 4000K until 17:00.



(a)



(b)



(c)

Figure 3: (a) Temporal changes in rectal temperature during sleep (M+S.D.). A: Japan Industry Standard (JIS) mode; 750 lux with 5000K, constant; B: Saving Energy (SE) mode; 400 lux with 5000K, constant; C: Eco Circadian Light Control Program (ECLCP); 750 lux with 6000K until 14:00 followed by being lowered to 400 lux with 4000K until 17:00. (b) Decrement of rectal temperature from 1:30am to nadir during sleep (M ± S.D.). A: Japan Industry Standard (JIS) mode; 750 lux with 5000K, constant; B: Saving Energy (SE) mode; 400 lux with 5000K, constant; C: Eco Circadian Light Control Program (ECLCP); 750 lux with 6000K until 14:00 followed by being lowered to 400 lux with 4000K until 17:00. (c) Increment of rectal temperature from nadir to 7:30am during sleep (M ± S.D.). A: Japan Industry Standard (JIS) mode; 750 lux with 5000K, constant; B: Saving Energy (SE) mode; 400 lux with 5000K, constant; C: Eco Circadian Light Control Program (ECLCP); 750 lux with 6000K until 14:00 followed by being lowered to 400 lux with 4000K until 17:00.

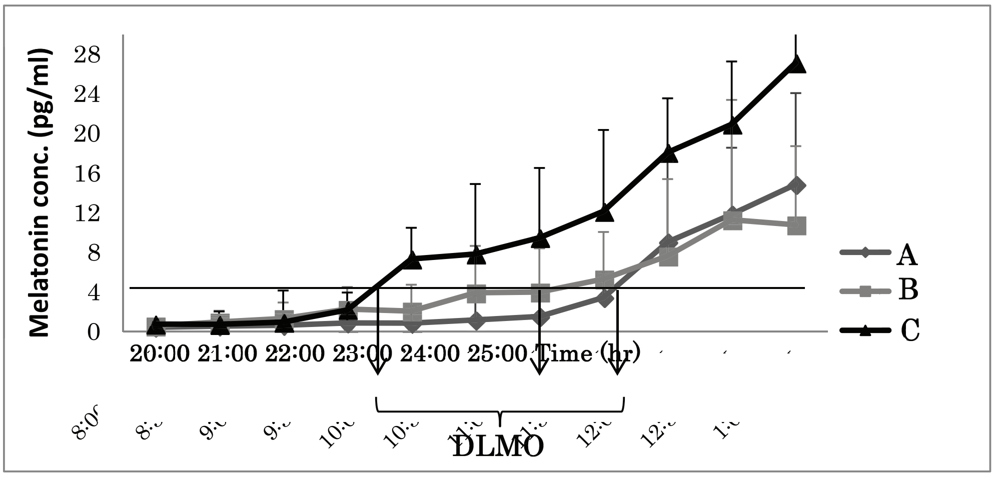


Figure 4: Dim light melatonin onset (DLMO) and melatonin secretion before bedtime (M + S.D.). A: Japan Industry Standard (JIS) mode; 750 lux with 5000K, constant; B: Saving Energy (SE) mode; 400 lux with 5000K, constant; C: Eco Circadian Light Control Program (ECLCP); 750 lux with 6000K until 14:00 followed by being lowered to 400 lux with 4000K until 17:00.

There were significant differences in DLMO across the lighting conditions, and the phase was significantly advanced by exposure to ECLCP. ECLCP before bedtime was associated with a significantly greater increase in melatonin than in either JIS or SE mode.

Among subjective evaluations, only responses to the item regarding bright–dark showed a tendency to differ between lighting conditions ($p < 0.1$). SE mode was perceived as darker than JIS mode and ECLCP. Responses to the other 7 items, meanwhile, showed no difference across lighting conditions.

PSG during the first half of sleep tended to show a lower number of epochs of stage 3 sleep in SE mode compared with JIS mode and ECLCP, but this did not reach the level of significance ($p < 0.1$).

4. Discussion

The purpose of this study was to examine the validity of time-dependent controls for illuminance and color temperature of office lighting with respect to comfort, energy efficiency, and circadian rhythms. While many studies have examined how light intensity and color temperature affect alertness and work efficiency [5–7], few have sought to examine relationships between office lighting, circadian rhythms, and energy savings.

Shimoda et al. [2] developed CPTOP as an index of quantitative and objective evaluation of office performance. CPTOP was employed as a simulation of general office work in this study. Although CPTOP results with respect to number of sorted slips and average sorting rate were not significantly different across lighting conditions, significant differences in the arousal level obtained from the early component of CNV amplitude were found, showing lower arousal levels in SE mode than those observed in either JIS mode or ECLCP. It was thought that the lower arousal level in SE mode would be reflected in a higher number of errors in the CNV paradigm in comparison with the other lighting conditions. Although the effect of lighting condition on CPTOP performance did not reach the level of significance, CNV paradigm results suggest that daily productivity in office settings might be affected by lighting intensity of less than 400 lx. Drowsiness observed after lunch, often called 'post-lunch dip', was indicated by both CNV amplitude in JIS mode and CPTOP in SE mode results, but not ECLCP.

It is well known that circadian rhythm is primarily entrained by natural light cycles. Therefore, it has been hypothesized that lighting conditions normally seen in an office, which involve constant intensity and color temperature, would make the rhythm vague [8]. In this study, the amplitude of rhythm was evaluated by temporal changes in rectal temperature during sleep; circadian phase advance due to daytime lighting conditions was assessed via dim light melatonin onset (DLMO); and sleep architecture was evaluated by PSG [2].

The decrease in rectal temperature from bedtime to the nadir was smaller in SE mode than in JIS mode and ECLCP. The increase from the nadir to wake-up time was also smallest in SE mode and greatest in ECLCP. There was no significant difference in decrement of rectal temperatures between JIS mode and ECLCP. However, rectal temperature had already begun to decrease prior to bedtime in ECLCP, which is possibly explained by significantly advanced DLMO and an associated increase in melatonin secretion [9] in ECLCP. In fact, the decrease in rectal temperature between 24:00 and nadir, was significantly greater in ECLCP than in JIS mode. Therefore, it was likely that the overall decrease in rectal temperature was also greatest in ECLCP, which indicates that the amplitude of body temperature rhythm was also greatest in ECLCP. This implication is supported by previous studies showing that high illuminance with blue-enriched light in the morning, as in ECLCP, would cause a greater increase in melatonin secretion at night [10, 11]. This may in turn lead to a larger increase and decrease in core body temperature during sleep.

DLMO in the ECLCP condition (Fig. 4) was significantly advanced relative to JIS and SE modes. This suggests that exposure to blue-enriched light in the morning, as in ECLCP conditions (750 lx and 6000 K), would effectively stimulate circadian phase to a great extent than would JIS mode (750 lx and 5000 K) [12]. In addition to higher color temperature, high light intensity would also weaken inhibition of melatonin secretion; as a result, melatonin secretion would increase before bedtime, which might cause lower rectal temperature at nadir.

The number of epochs of stage 3 sleep during the first half of sleep tended to be lower in SE mode, but this did not reach the level of significance. However, our previous study indicated that this is possible [13], and would be more likely when workers are exposed to a higher color temperature of light at night [14]. Such results suggest that lower intensity light (i.e., less than 400 lx) in office settings might affect sleep architecture, especially slow-wave sleep.

5. Conclusions

The results of this study indicate that light intensities of less than 400 lx in office settings might affect not only alertness and productivity, but also the amplitude and phase of circadian rhythms, including sleep composition. To maintain appropriate circadian rhythms and effectively save energy, it would be best to use a high intensity and color temperature of light in the morning before lowering these values in the afternoon, as in ECLCP condition. This is in line with the aims of JIS office light recommendations in maintaining arousal level and work efficiency.

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