

Effect of Illuminance and Color Temperature on Lowering of Physiological Activity

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Abstract. To investigate how illuminance and color temperature in illumination affect the autonomic nervous system and central nervous system in conditions tending to lower physiological activity, and with an ordinary residential setting in mind, we performed an experiment on 8 healthy male subjects. The experimental conditions consisted of 4 conditions provided by a combination of 2 levels of color temperature (3000 K, 5000 K) and 2 levels of illuminance (30 lx, 150 lx). Physiological measurement was carried out during a process of 22 minutes of light exposure followed by 20 minutes of sleep in darkness. Heart rate variability (HRV) was used as an index of the autonomic nervous system, and alpha attenuation coefficient (AAC) and mean frequency of EEG were used as indices of the central nervous system. Subjective evaluation of drowsiness during the experiment was also carried out immediately following the 20 minutes sleep. No effect on HRV from illumination was noted, but significantly ($p < 0.05$) lower values for AAC were obtained under 3000 K conditions than 5000 K conditions in measurements during the first half of light exposure (Session 1). During alpha attenuation testing, significantly ($p < 0.05$) lower values for mean frequency in the q - b EEG bandwidth were also obtained under 3000 K conditions than 5000 K conditions, but that pattern persisted in measurement during the second half of light exposure (Session 2). Subjective drowsiness was also higher under 3000 K conditions than 5000 K conditions. These results suggest that low color temperature light creates a smooth lowering of central nervous system activity, and that low color temperature illumination can be used effectively in a bedroom or other such environment where it is desirable to facilitate lowered physiological activity.

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Introduction

Common experience teaches that illuminance, or light quantity, and color temperature, or light quality, make various psychological impressions on humans. For example, the high color temperature, high illuminance light of a clear midday sky creates an energetic mood, while the low color temperature, low illuminance light of candles at night creates a relaxed mood. The research of Kruithof (1941) on such psychological, interactive effects of color temperature and illuminance produced a curve illustrating a range of comfort, with illuminance as the vertical axis and color temperature as the horizontal. Even present-day discussions of psychological comfort in illumination make more than occasional reference to these results. Though Kruithof's research has not been formally verified, recent research concerned with its physiological effects, and specifically those on the autonomic nervous system and the central nervous system, is being carried out in order to investigate everyday illumination of greater comfort.

With regard to illuminance effect, Sugimoto (1980, 1981) and Sugimoto and Hataoka (1986) reported that illuminance higher than 320 lx–560 lx increased mean heart rate rapidly in illuminated environments from 10 lx to 2000 lx. Sato et al. (1996) reported that conditions of 3125 lx increased heart rate in illuminated environments from 200 lx to 3125 lx. With regard to color temperature effect, Mukae and Sato (1992) investigated heart rate variability (HRV) as an index of effects on the autonomic nervous system in illuminated environments of color temperature 3000 K, 5000 K, and 6700 K and reported higher autonomic nervous activity under 6700 K conditions than 3000 K conditions. Deguchi and Sato (1992) investigated contingent negative variation (CNV) as an index of effect on the central nervous system and reported a higher level of central nervous system activity under 7500 K conditions than 3000 K conditions. Iwakiri et al. (1997) obtained similar results. With regard to multiple effect of illuminance and color temperature, Küller and Wetterberg (1993) reported that EEG α -waves decreased throughout a 1-day period under 1700 lx conditions created by daylight

color fluorescent lamps, in illuminated environments from 450 lx to 1700 lx created by daylight color and warm white color fluorescent lamps.

To summarize these results, it may be stated that high color temperature, high illuminance lighting in particular stresses and activates the autonomic nervous system (specifically, the sympathetic nervous system) and the central nervous system. However, all of this research conceptualized an office space, with experiments carried out under conditions of high physiological activity (autonomic and central nervous system activity is high) conducive to various mental tasks, and there is no existing research concerning the physiological effects of illumination under circumstances of low physiological activity akin to a bedroom or other leisure space in an ordinary residence. The importance of such research and the need for thorough investigation is indicated by the fact that at night the ordinary residential space relies almost entirely on artificial illumination differing from daylight available during the day, as well as the long-term usage of such illumination in daily living.

Consequently, our research conceptualized a bedroom in an ordinary residence and investigated how the illuminance and color temperature of illuminating light affect the autonomic nervous system and the central nervous system in conditions leading to lowered physiological activity. We discuss optimal illumination in these conditions.

Methods

Subjects

A total of 8 healthy males age 25–30 years (mean age 27.9 years) participated in the experiment as subjects.

Experimental conditions

Experimental conditions consisted of 4 conditions provided by a combination of 3000 K and 5000 K color temperature levels and 30 lx and 150 lx illuminance levels. The light source consisted of three-band, round fluorescent lamps of color rendering index 88 installed at the center of an experimental room ceiling, color temperature conditions were established by the exchange of lamps and the setting of illuminance was accomplished by light-adjustment control. Illuminance was set as that on the floor at the center of the experimental room, directly beneath the light source. Temperature in the experimental room was controlled at 25 C, and a reclining seat for subject use was provided at the center of the experimental room. Subjects could lower the back of the reclining seat to allow sleeping, but its angle was set within a range at which the light source did not impinge directly on the visual field of the subject.

Measurements

In a state where the arousal level is high, numerous

α -waves appear on the EEG when eyes are closed, but on opening the eyes they disappear. On the other hand, in a state of drowsiness, α -waves do not come to appear when eyes are closed, but on opening the eyes they appear. Based on this phenomenon, Michimori et al. (1994) established Alpha Attenuation Test (AAT) which allows to quantify the central nervous activity. In AAT, Alpha Attenuation Coefficient (AAC) is calculated by alternating closed eyes with open eyes and dividing α -wave power at closed eyes by α -wave power at open eyes. AAC rises when the arousal level rises, and falls when arousal level falls. In this study, AAC and mean frequency of EEG were used as indices of central nervous system activity, and heart rate variability (HRV; Kobayashi et al. 1999) was used as an index of autonomic nervous system activity. EEG were recorded by monopolar lead from the Cz and Pz locations according to the international 10/20 system, using a Ag/AgCl electrode and the left earlobe as a non-linked electrode reference. A digital multi-purpose electroencephalograph (NEC SYNAFIT5000) was used for amplification with a time constant of 0.3 seconds and an upper cutoff frequency of 30 Hz. In AAT, 1 minute eyes-closed resting and 1 minute eyes-open resting were repeated three times reciprocally, and EEG were digitized on-line (sampling frequency 1 kHz). Electrocardiogram was recorded by dual chest electrodes and similarly amplified by the aforementioned multipurpose electroencephalograph with a time constant of 1.0 seconds and an upper cutoff frequency of 100 Hz. During HRV measurement, respiratory regulation to a 0.25 Hz period was accomplished by sampling voices, and the electrocardiogram was digitized on-line (sampling frequency 1 kHz). Subjective evaluation of drowsiness during the experiment was carried out by 5-grade evaluation from 0 to 4 (0-not drowsy, 4-extremely drowsy).

Procedure

The experiment was carried out in afternoon time frames conducive to a lowered arousal level. After attachment of electrodes, control session measurement was carried out with the subject seated in a chair outside the experimental room (illuminance 700 lx, color temperature 5000 K). After completion of measurement, the subject was asked to enter the experimental room which the lighting condition was set; 1 minute eyes-open resting followed by Session 1 measurement was carried out; further 1 minute eyes-open resting was interrupted to carry out Session 2 measurement; and finally 20 minutes sleep was allowed (in darkness). In each measurement session, 1-minute eyes-open resting was interrupted and AAT (6 minutes) and HRV measurement (3 minutes) were carried out. With regard to measurement after entering to the experimental room, subjects were directed to, "Take part in the experiment by relaxing with the idea of falling asleep about 20 minutes after entering the sleeping room".

Data analysis

Fast Fourier transformation (FFT) was used for frequency analysis of EEG during AAT. FFT was carried out for each 10.24 seconds of data (1024 points), 6 frequency spectra were averaged, and a 1-minute mean frequency spectrum was calculated. An α -wave (8.0–13.0 Hz) power value was calculated from the mean frequency spectrum obtained, and the AAC was calculated by dividing mean α -wave power at closed eyes by mean α -wave power at open eyes. Given that the occipital region manifests α -waves strongly, AAC was studied using Pz location data. To investigate EEG frequency structure during AAT, a frequency was calculated which halved the power of the frequency bandwidth extending from q -waves to b -waves (4.0–25.0 Hz) in the frequency spectrum obtained; i.e., a mean frequency. Given that α -waves are strongly manifested at the occipital region and q -waves at the parietal and frontal regions, Cz/Pz mean values were used to study these indices.

R-wave detection in ECG data was performed during HRV measurement, successive R-R interval data was calculated, interpolation was performed by the instantaneous heart rate (IHR) method according to DeBoer et al. (1985), R-R interval time-series data was created, and sampling was carried out at a sampling frequency of 2 Hz. Frequency analysis by FFT was performed on the 256-element R-R interval data obtained, and a frequency spectrum was calculated. Two components are present in a frequency spectrum of heart rate variability. The first is Mayer wave sinus arrhythmia (MWSA), a sinus arrhythmia related to Mayer waves in blood pressure presenting nearly 0.1 Hz peaks, and the other is respiratory sinus arrhythmia (RSA), a respiratory arrhythmia presenting peaks matched to respiratory frequency (Sayers 1973). The power of the 0.05–0.15 Hz MWSA component (LF) and the 0.15–0.40 Hz RSA component (HF) were determined from the frequency spectrum obtained, and LF/(LF+HF) and LF/HF were calculated. During HRV measurement, mean frequency in the EEG frequency bandwidth extending from q -waves to b -waves was also calculated, as in AAT.

Frequency analysis by FFT of EEG data during the 20-minute sleep interval was performed as during AAT, 1-minute mean frequency spectra were calculated, and mean frequency in the frequency bandwidth extending from q -waves to α -waves (4.0–13.0 Hz) was calculated.

Statistics

All data was indicated using mean values and standard errors, repeated measures analysis of variance (repeated measures ANOVA) was used for recognition of significance, and $p < 0.05$ was taken as the level of significance. The experiment accounted for circadian rhythm in that a given subject participated in the experiment during the same

time slot in each instance, in pursuit of a consistent physiological condition. However, the results showed some disparity even in control session measurements preceding exposure to the experimental condition, requiring a consideration of pre-experiment circumstances. Accordingly, a regression analysis of all evaluation indices was performed with control session measurements as the independent variable and Session 1 and 2 measurements as dependent variables, and if a significant relationship was found, the regression equation was used for correction according to control values.

Results

Fig. 1 shows changes in AAC. By session, AAC exhibited a declining trend over time, from the control session through Sessions 1 and 2. In terms of illumination conditions, lower values were noted in Session 1 under 3000 K conditions than 5000 K conditions and under 30 lx conditions than 150 lx conditions, but in Session 2 this trend virtually disappeared. Regression analysis results showed no significant correlation between control session measurements and Session 1 and 2 measurements, and when Session 1 and 2 measurements were used in repeated measures ANOVA without correction according to control session measurements, measurement session causality was highly significant ($p < 0.01$). Neither the illuminance nor the color temperature factor was causally significant as an effect of illumination, but the color temperature factor displayed a low p -value of $p = 0.0576$. However, our measurements reflect frequent instances in which the subject had become highly drowsy by the time the experiment progressed to Session 2, resulting in poor accuracy of eye opening/closing control during AAT. As described above, AAC is a comparison of α -wave power when eyes are closed and open, and when the accuracy of eye opening and closing control declines, the accuracy of evaluation can be taken to decline. Session 2 was therefore excluded from analysis as bad data, and repeated measures

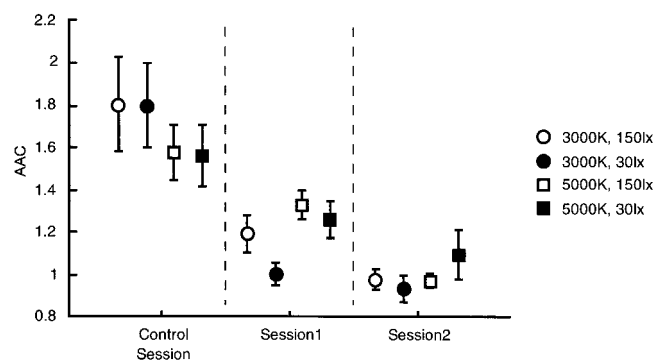


Fig. 1 Changes in AAC (Pz location). Means and standard errors are shown.

Table 1 Results of repeated measures ANOVA on AAC at Session 1

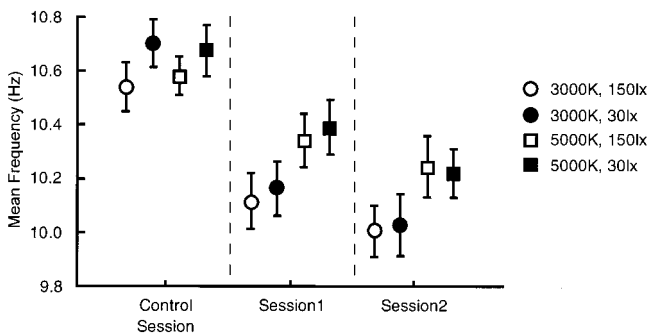
Factor	D.F	S.S.	M.S.	F	p
Color Temperature: A	1	.302	.302	6.680	.0362*
Illuminance: B	1	.129	.129	4.418	.0737
Subject: C	7	.281	.040		
A*B	1	.029	.029	.470	.5152
A*C	7	.317	.045		
B*C	7	.205	.029		
A*B*C	7	.425	.061		

*: p<0.05.

Table 2 Results of repeated measures ANOVA on mean frequency in the *q-b* EEG bandwidth during AAT

Factor	D.F	S.S.	M.S.	F	p
Color Temperature: A	1	2.819	2.819	6.412	.0391*
Illuminance: B	1	.031	.031	.216	.6564
Session: C	1	.993	.993	3.920	.0882
Subject: D	7	102.725	14.675		
A*B	1	.009	.009	.027	.8749
A*C	1	.002	.002	.027	.8744
A*D	7	3.078	.440		
B*C	1	.036	.036	.084	.7806
B*D	7	1.022	.146		
C*D	7	1.773	.253		
A*B*C	1	.009	.009	.046	.8359
A*B*D	7	2.397	.342		
A*C*D	7	.524	.075		
B*C*D	7	2.988	.427		
A*B*C*D	7	1.382	.197		

*: p<0.05.

**Fig. 2** Changes in mean frequency in the *q-b* EEG bandwidth during AAT. Means and standard errors are shown.

ANOVA was performed on Session 1 data alone. In the results, the color temperature factor was significant, and illuminance was not significant but displayed a low p-value of 0.07. Table 1 presents the ANOVA results.

Fig. 2 presents changes in mean frequency in the *q-b* EEG bandwidth during AAT. As in AAC, a pattern of decline over time was noted in the sessions. Effects from illumination showed no difference according to illuminance

conditions, but lower values under 3000 K conditions than 5000 K conditions. Results from regression analysis showed a significant correlation between control session measurements and Session 1 and 2 measurements; thus, data obtained from the control session was used to correct data obtained in Session 1 and 2, and in repeated measures ANOVA, the color temperature factor was significant. Table 2 presents the ANOVA results.

Fig. 3 presents changes in LF/(LF+HF) in HRV. While a lowering of values was seen between the control session and Session 1, this is deemed largely due to the influence of the change in autonomic nervous system activity resulting from the change in posture. Each illumination condition presents a great disparity in results, and no effect characteristic of illumination was observed. Similarly, there was no observable effect from illumination on LF/HF or LF and HF. Fig. 4 presents changes in mean frequency in the *q-b* EEG bandwidth during HRV measurement. A decline in values was observed between the control session and Session 1, but a pattern of decline was not observed between Sessions 1 and 2. Effects from illumination were also not as distinct as during AAT; a pattern of decline was noted under 3000 K conditions as in AAT, but that pattern

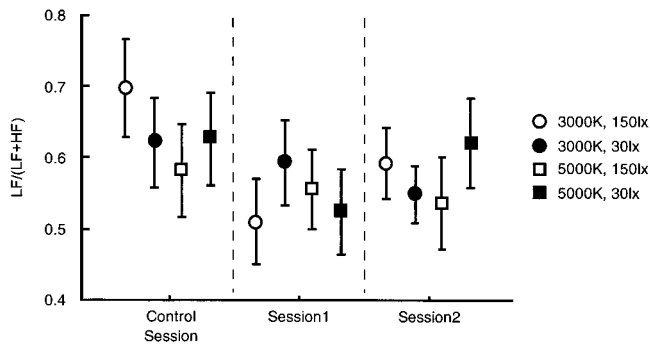


Fig. 3 Changes in LF/(LF+HF) in HRV. Means and standard errors are shown.

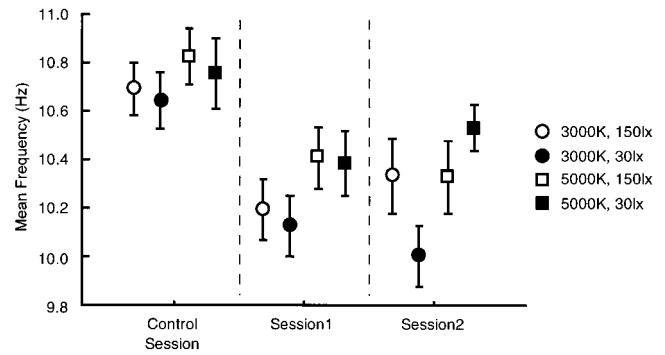


Fig. 4 Changes in mean frequency in the Q-b EEG bandwidth during HRV measurements. Means and standard errors are shown.

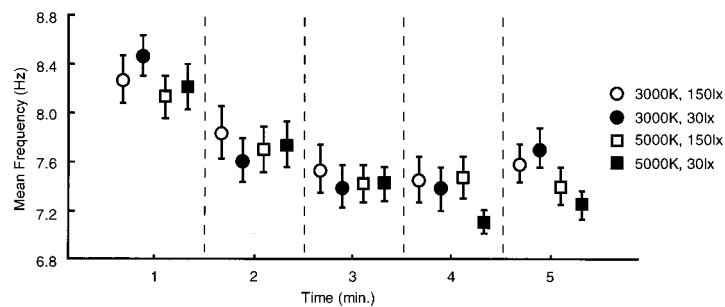


Fig. 5 Changes in mean frequency in the q-a EEG bandwidth during 5 minutes following the onset of sleep (the end of the light exposure). Means and standard errors are shown.

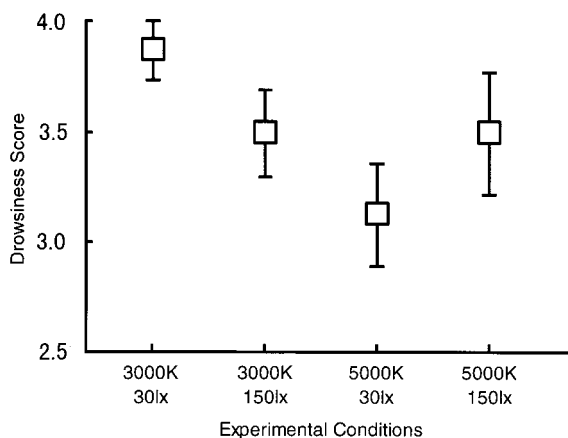


Fig. 6 Changes in subjective drowsiness score. Means and standard errors are shown.

disappeared in Session 2. ANOVA results were insignificant for all factors.

Fig. 5 presents changes in mean frequency in the q-a EEG bandwidth during 5 minutes following the onset of

sleep (the end of the light exposure). The results show a pattern of decline immediately after the onset of sleep, but no effect characteristic of illumination was observed in this lowering process.

Fig. 6 presents changes in subjective drowsiness during the experiment under each illumination condition. Among all conditions, subjective drowsiness during the experiment was the highest under conditions of 3000 K and 30 lx, and the lowest under conditions of 5000 K and 30 lx.

Discussion

The Multiple Sleep Latency Test (MSLT; Carskadon and Dement 1982) is widely known as a method for quantifying arousal level as an index of EEG activity. However, the recumbent position measurement that the MSLT entails is problematic for application to various environments under evaluation, and its assessment of sleep stages by visual observation demands real-time performance. Both of these factors make measurement difficult for all but sleep researchers highly practiced in sleep stage assessment. The AAT was developed for these reasons and has been demonstrated as highly reliable in

quantification of arousal level, with a high correlation to MSLT results (Michimori et al., 1994). In the present experiment, AAC declined over time. These results suggest that subjects were successfully controlled, and that a setting was created which lowered the subjects' arousal level. In terms of illumination effect, AAC values were conspicuously lower under 3000 K conditions than 5000 K conditions in Session 1 (Fig. 1), and this result suggests that lowering of central nervous activity is smoother under 3000 K conditions. Mean frequency of EEG was also used as another index of central nervous activity. In the waking state, EEG consist mainly of *a*-waves and *b*-waves, but as sleepiness sets in and arousal level declines, *a*-waves also appear readily when the eyes are closed, and there is a gradual shift toward the direction of *q*-waves. As a result, a decline in the mean frequency in the bandwidth from *q*-waves to *b*-waves can be taken to reflect a decline in arousal level immediately prior to the onset of sleep. Our results also noted a pattern of conspicuous decline in mean frequency under 3000 K conditions compared to 5000 K conditions (Fig. 2), suggesting a smoother lowering of central nervous activity under 3000 K conditions, as in the AAC results. This effect also persisted into Session 2, and this result suggested that a color temperature effect on the central nervous system persisted into Session 2.

However, color temperature effect on EEG mean frequency under respiratory regulation during HRV measurement was not as distinct as during AAT (Fig. 4). The research of Deguchi and Sato (1992) observed differences in CNV amplitude between 3000 K and 7500 K conditions, but no difference was observed between 3000 K and 5000 K conditions. Based on the fact that subjects performed a highly taxing odd-ball task during CNV measurement, it may be the case that the effect of color temperature differs depending on whether the subject is presented with task execution or a similar burden.

In HRV, the MWSA component (LF) is taken to reflect both sympathetic nervous and parasympathetic nervous activity in the autonomic nervous system, and the RSA component (HF) is taken to reflect parasympathetic nervous activity (Pomeranz, et al., 1985); thus, LF/(LF+HF) and LF/HF and the like are widely used in environmental evaluations as indices of autonomic nervous activity. The fact that our results failed to note an effect of illumination on HRV (Fig. 3) and the fact that the research of Mukae and Sato (1992) also observed no effect on the autonomic nervous system between 3000 K and 5000 K may signify that this range of color temperature has essentially no effect on the autonomic nervous system under circumstances tending to lower central nervous activity. However, in light of the fact that respiratory regulation in measurement of HRV imposes a higher burden of task execution than eye opening and closing in AAT, it may be the case that conditions resulting in low physiological activity among subjects were not achieved

during measurement of HRV. Possible evidence supporting this conjecture is the lack of reduction in LF/(LF+HF) and EEG mean frequency during measurement of HRV between Session 1 and Session 2, and the less distinct effect of illumination on EEG mean frequency than during AAT (Figs. 3, 4). Consequently, there is justification for further study using other evaluative indices which do not require a task in order to investigate the effect of illumination on the autonomic nervous system in such conditions. We also ask whether the lack of any observed effect of illumination on EEG during sleep (Fig. 5) is similar to an effect of the immediately prior HRV measurement.

Subjective drowsiness was also higher under 3000 K conditions than 5000 K conditions (Fig. 6), presenting results akin to those for EEG. Under 5000 K conditions, the effect of illuminance was the reverse of that under 3000 K conditions, with low subjective drowsiness reported under 30 lx conditions. This may represent the effect of an unpleasant "cold" image in particular under high color temperature/low illuminance conditions, as suggested by Kruithof (1941). From the standpoint of relatedness to the physiological indices, 5000 K conditions in AAC resulted in virtually no reduction of values at 30 lx compared to 3000 K conditions, but the lack of observed significance in ANOVA for an interaction between illuminance and color temperature factors fails to indicate a strong correlation with physiological effects.

Our results noted almost no effect from illuminance compared to that from color temperature. The research of Sugimoto (1980, 1981), Sugimoto and Hataoka (1986), Küller and Wetterberg (1993) and Sato et al. (1996) reported an effect from illuminance on the autonomic nervous system and central nervous system, though under task conditions. However, this effect was strikingly manifested under conditions of illuminance higher than those established by our experimental conditions. Given that the room illuminance established in an ordinary residence is at most some 100–200 lx, apart from study lamps and other task illumination, we surmise that the effect of color temperature is greater than that of illuminance in an ordinary residential bedroom or similar environment where a lowering of physiological activity is desirable, and we therefore find the use of low color temperature illumination more important than the reduction of illuminance. Subjective drowsiness results also indicate that reduction of illuminance without reduction of color temperature should be avoided. The fact that the effect of low color temperature illumination is manifested in a short-duration exposure of 1–7 minutes after room entry further suggests that conditions akin to those in our experiment are encountered frequently in everyday life. The indistinct effect of color temperature on EEG during respiratory regulation may also have other implications in spaces where work is performed. Further study on this topic is needed.

In Japan, 5000 K or higher color temperature fluorescent lamps provide the bulk of illumination for ordinary residential use. For reasons including quality of atmosphere, recent years have seen a reappraisal of low color temperature illumination of approximately 3000 K, and low color temperature fluorescent lamps are also available, but Japanese show a continued preference for high color temperature illumination, and low color temperature illumination has yet to take hold. We anticipate that the existence and importance of the physiological effect of color temperature that we have reported here will, to some slight extent, hasten a wider social recognition of this issue.

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