Differential Effect of Light Emitting Diode Light on Electroencephalographic Oscillations in Young and Old Healthy Subjects

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Objectives: To investigate brain oscillatory characteristics according to brightness and color temperature of light emitting diode (LED) light in young and elderly subjects. **Methods:** We analyzed 22 young (age, 29.0 ± 5.2 years) and 23 elderly (age, 64.8 ± 4.5 years) healthy subjects. A LED light source was used with a combination of two color temperature (6,500 K vs. 3,000 K) and two brightness (700 lx vs. 300 lx) conditions. Participants were exposed to each light condition in relaxed wakefulness. Then, we analyzed power spectral density and functional connectivity from eye-open electroencephalography. **Results:** A main effect of brightness on delta ($p=0.044$) and theta ($p=0.038$) power was significant in the elderly subjects. Bright light enhanced delta and theta power in the frontal region. By contrast, power spectral density of young subjects was affected by color temperature; high color temperature significantly increased beta-band power of the central region ($p=0.034$). Regarding functional connectivity, a significant effect of color temperature was observed in delta ($p=0.006$) and beta ($p=0.046$) frequencies. High color temperature light enhanced beta connectivity of young subjects ($p=0.007$), while not affecting that of elderly subjects ($p=0.979$). **Conclusions:** The present study demonstrated that spectral power and functional connectivity as well as subjective feelings are affected by the brightness and color temperature of LED light. These results might help us to understand the neurophysiological effects of light and identify the optimal indoor lighting conditions for an individual's environment.

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Key Words: Power spectral density, Functional connectivity, Electroencephalography, Light emitting diode, Brightness, Color temperature.

Introduction

Light has profound effects on human health.¹ Endogenous circadian rhythms affect physiological processes of major organ systems as cardiovascular, metabolic, and gastrointestinal functions as well as sleep-wake cycle.² Light, known as a dominant zeitgeber, is essential for synchronization or entrainment of endogenous circadian system to the 24-hr light-dark cycle.³ Disruption of the circadian rhythm is associated with various diseases, such as insomnia, depression, cardio-

vascular diseases, and cancers.⁴⁻⁶ Moreover, light have an effect on mood, perception, and cognition.^{7,8} Brightness and color temperature are important lighting conditions affecting subjective perception and cognitive performance. Bright light exposure during the daytime reduces sleepiness and improves psychomotor vigilance task performance.⁷ Exposure to bright light was also reported to attenuate cognitive deterioration in elderly patients with dementia.⁹ On the other hand, color temperature is a measure of color appearance provided by a light source; low color temperature is red-enriched white with warm and stable mood, whereas high color temperature is red-enriched white with cool and active atmosphere.¹⁰ High color temperature light was shown to increase levels of arousal and

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concentration as well as psychological well-being.¹¹

Although there has been substantial research into the effects of lighting conditions on mood and behavior, previous investigations were mostly based on subjective measures such as self-reported questionnaires. Accordingly, there has been relatively little evidence objectively showing that brain activities are altered by different lighting conditions. Electroencephalography (EEG) is an electrophysiological method to record the brain activity and its change according to different lighting conditions.¹² Because prior EEG studies were limited to investigations for young subjective,^{13–15} little is known about neurophysiological characteristics of the lighting effects in elderly subjects. Therefore, herein, we investigated brain oscillatory characteristics according to brightness and color temperature of light by analyzing power spectral density and functional connectivity derived from resting-state EEG recordings. Furthermore, we compared the lighting effects between young and elderly subjects to determine age-dependent responses to brightness and color temperature.

Methods

Subjects

We prospectively recruited healthy young ($n=30$, age range 20–39 years) and old ($n=30$, age range 60–76 years) volunteers through advertisement from February to June 2016. Exclusion criteria were history of any neurological or psychiatric disorders, significant head trauma, and brain surgery. Those who took medication within the last two weeks, which can affect EEG recordings, such as antiepileptic drugs, sleeping pills, and antidepressants, were also excluded. All participants visited the Department of Neurology of the Seoul National University Hospital and were screened for the selection criteria. All subjects gave written informed consent before enrollment into the study. Among 60 subjects enrolled, 8 young and 7 old subjects were excluded from the analysis because of poor EEG data quality. Finally, data from 22 young (mean age, 29.0 ± 5.2 years; men 50%) and 23 elderly (mean age, 64.8 ± 4.5 years; men 82.6%) subjects were analyzed in this study. This study was approved by the Institutional Review Board of the Seoul National University Hospital (H-1601-043-733) and was conducted in compliance with the Declaration of Helsinki and the Good Clinical Practice guidelines.

Lighting condition

We used four different light conditions as a combination of color temperature (6,500 K vs. 3,000 K) and brightness (700 lx vs. 300 lx): high-bright (6,500 K, 700 lx); high-dark (6,500 K, 300 lx); low-bright (3,000 K, 700 lx); and low-dark (3,000 K, 300 lx) light. These light parameters were chosen within the

range of indoor lighting conditions which are commonly used in the real world. The experimental space (width 2 m, length 2.5 m, height 2.7 m) was shielded from ambient light. Light emitting diode (LED) light panels (Mimilighting, Incheon, Korea) were suspended from the ceiling. We used a controller to regulate color temperature and brightness of LED light per session. The lighting condition was checked at desk level (0.7 m).

For each light condition, subjects first took a rest in a light-less condition for 5 min. Then, LED light of specific parameters was presented for 5 min when subjects opened and closed their eyes alternately every 1 min (Fig. 1A). EEG recordings during the last 4 min after the light was turned on were used for analysis of spectral power and functional connectivity. The order of the light conditions was counterbalanced across subjects (Fig. 1B). For 4 lighting condition with the repeated measures design, there are 24 orders of light exposure. We added 6 more orders to make 30 orders of lighting condition for 30 participants. Although it is not complete randomization, we used this counterbalance design to minimize the effect of the order of light condition exposed to the subjects. Subjective feelings on sleepiness, refreshment, comfort, and happiness were evaluated at the end of each light condition. The degree of sleepiness was evaluated using the Stanford sleepiness scale ranging from 1 to 7.¹⁶ Subjective refreshment, comfort, and happiness were measured by using 11-point Likert scales with 0 indicating “not at all” and 10 indicating “extremely”.

EEG recording and pre-processing

EEG was recorded using a 64-channel recording system (Grass Technologies, Quincy, MA, USA) with 60 cap-based electrodes (Quick-Cap, Charlotte, NC, USA) that were located according to the international 10–20 system. Impedances were kept below 10 k Ω in all electrodes. EEG recordings were sampled at 400 Hz and referenced to an average reference. A bandpass filter was set between 0.5–70 Hz. We thoroughly inspected EEG recordings and selected 30 artifact-free epochs of 2-s duration from eye-open resting-state EEG for each light condition.

Selected EEG data were pre-processed and further analyzed for power spectral density and functional connectivity using MATLAB (MathWorks, Natick, MA, USA). We applied 60-Hz notch filter and interpolated bad EEG channels. Then, we performed independent component analysis decomposition and removed components containing ocular movement, heartbeat, and muscle artifacts. The current source density transformation was employed to enhance EEG spatial resolution and minimize the volume conduction effect. In addition, EEG data were demeaned and detrended to remove nonstationarity of the time series mean.

Figure 1. Experimental design. (A) Schematic illustration of exposure to each lighting condition. (B) Schematic illustration of a counterbalanced design for the order of lighting conditions. Each subject is exposed to all 4 lighting conditions in a different order.

Power spectral analysis

Spectral power analysis was performed using a fast Fourier transformation with the Welch's method (1-s hamming window, 50% overlap).¹⁷ Frequencies were divided into delta (0.5–4 Hz), theta (4–8 Hz), alpha (8–12 Hz), and beta (12–30 Hz) bands with a frequency resolution of 0.25 Hz. Electrodes were grouped into three topographical regions as previously described¹⁸: the frontal (AF3, AFz, AF4, F5, F3, F1, Fz, F2, F4, and F6); central (FC5, FC3, FC1, FCz, FC2, FC4, FC6, C5, C3, C1, Cz, C2, C4, C6, CP5, CP3, CP1, CPz, CP2, CP4, and CP6); and the parietal (P5, P3, P1, Pz, P2, P4, P6, PO3, POz, and PO4) regions. Power spectral density was expressed in dB.

Functional connectivity analysis

To measure EEG functional connectivity, we computed the weighted phase lag index (wPLI).¹⁹ The wPLI is an improved index of phase synchronization compared to the phase lag index (PLI) in terms of increased power to detect changes in phase synchronization as well as reduced sensitivity to uncorrelated noise sources.²⁰ For functional connectivity analysis, we only used EEG data recorded from 21 electrodes according to the international 10–20 system. Briefly, the Hilbert transformation was applied to calculate the instantaneous phase for each time point. Then, we measured functional connectivity by averaging wPLI values over all 210 electrode pairs. The average wPLI for each subject was estimated for four fre-

quency bands: delta (0.5–4 Hz); theta (4–8 Hz); alpha (8–12 Hz); and beta (12–30 Hz) bands.

Statistical analysis

For power spectral density, we conducted repeated-measures analysis of variance (ANOVA). Within-subject variables included brightness (two levels: bright and dark), color temperature (two levels: high and low), and brain regions (three levels: frontal, central and parietal), while a between-subject variable was age groups (two levels: old and young). Thereafter, we conducted repeated-measures ANOVA per each age group. For functional connectivity and subjective evaluation data, within-subject variables included brightness (two levels: bright and dark) and color temperature (two levels: high and low), and between-subject variables were age groups (two levels: old and young). Both power spectral density and functional connectivity data were analyzed for each frequency band. When sphericity assumptions were violated, we applied the Greenhouse-Geisser correction to control for type 1 error rates. Multiple comparisons in post hoc analysis were corrected by the Bonferroni method. A two-tailed $p < 0.05$ was considered statistically significant. Statistical analyses were performed using SPSS version 18.0 (SPSS Inc., Chicago, IL, USA).

Results

Power spectral density of overall subjects

A significant interaction between brightness and age group was noted in theta power ($F_{1,43}=4.704$, $p=0.036$). In addition, there was a marginal interaction between brightness and group in delta frequency ($F_{1,43}=3.596$, $p=0.065$). However, for color temperature, no significant interaction effect with age group was observed in all frequencies. The results of repeated-measures ANOVA are summarized in Supplementary Table 1 (in the online-only Data Supplement).

Power spectral density of the elderly subjects

A main effect of brightness on delta-band power was significant in the old age group ($F_{1,22}=4.545$, $p=0.044$) (Table 1); bright light increased delta-band power compared to dark light. The effect of bright light was particularly significant in the frontal region ($p=0.013$) (Fig. 2A). However, the main effect of color temperature ($F_{1,22}=0.639$, $p=0.433$) and the interaction between brightness and color temperature ($F_{1,22}=1.293$, $p=0.268$) were not significant.

Similarly, theta-band power were significantly higher in bright light than in dark light ($F_{1,22}=4.882$, $p=0.038$). Analysis per region revealed that bright light particularly affected the frontal region ($p=0.031$) (Fig. 2B). However, there was no sig-

nificant main effect of color temperature ($F_{1,22}=0.166$, $p=0.687$) or the interaction between brightness and color temperature ($F_{1,22}=0.170$, $p=0.684$).

By contrast, power spectral density of alpha, beta bands were not affected by brightness or color temperature. In addition, there was no significant interaction between brightness and color temperature at these frequencies. Taken together, power spectral density of elderly subjects was influenced by brightness rather than color temperature. Bright light enhanced the delta- and theta-band power particularly in the frontal region.

Power spectral density of the young subjects

We observed a marginally significant effect of color temperature on beta power ($F_{1,21}=3.839$, $p=0.063$) (Table 2). Especially, high color temperature significantly increased beta-band power of the central region compared with low color temperature ($p=0.034$) (Fig. 3A). However, a main effect of brightness was not significant ($F_{1,21}=0.030$, $p=0.863$). Moreover, there was a significant interaction between brightness and color temperature ($F_{1,21}=6.484$, $p=0.019$). As shown in Fig. 3B, color temperature significantly affected the beta power under dark light ($p=0.012$) but not under bright light ($p=0.574$). Furthermore, post-hoc analyses revealed that high color temperature increased the beta-band power of frontal ($p=0.012$)

Table 1. Repeated-measures analysis of variance for power spectral density in elderly subjects

Factors	Delta		Theta		Alpha		Beta	
	F	p	F	p	F	p	F	p
Color temperature	0.639	0.433	0.166	0.687	0.168	0.686	<0.001	0.984
Brightness	4.545	0.044*	4.882	0.038*	0.503	0.486	0.379	0.545
Region	2.117	0.151	6.743	0.003**	33.176	<0.001**	0.841	0.417
Color temperature×brightness	1.293	0.268	0.170	0.684	0.798	0.381	0.114	0.739
Region×color temperature×brightness	1.105	0.326	0.350	0.707	0.804	0.420	0.057	0.906

Degree of freedom=1, 22. * $p<0.05$, ** $p<0.01$

Figure 2. Power spectral density of the elderly subjects according to brightness of light. (A) Delta-band (0.5–4 Hz) power. (B) Theta-band (4–8 Hz) power. Error bars indicate the standard errors of the mean. $n=23$. * $p<0.05$.

and central ($p=0.016$) regions compared with low color temperature under dark light.

At delta, theta, and alpha frequencies, however, there was no significant effect of different light conditions on power spectral density. In summary, power spectral density of young subjects was mainly affected by color temperature; high color temperature increased beta-band power in the central regions. Further, these effects of color temperature were partic-

ularly significant under the dark light condition.

Functional connectivity analysis

A significant main effect of color temperature on functional connectivity was observed in delta ($F_{1,43}=8.428$, $p=0.006$) and beta ($F_{1,43}=4.207$, $p=0.046$) frequencies; high color temperature light increased EEG functional connectivity compared to low color temperature light (Fig. 4A). Furthermore, we

Table 2. Repeated-measures analysis of variance for power spectral density in young subjects

Factors	Delta		Theta		Alpha		Beta	
	F	<i>p</i>	F	<i>p</i>	F	<i>p</i>	F	<i>p</i>
Color temperature	1.219	0.282	3.238	0.086	1.026	0.323	3.839	0.063
Brightness	0.465	0.503	1.168	0.292	1.780	0.196	0.030	0.863
Region	25.447	<0.001**	26.333	<0.001**	14.033	<0.001**	26.406	<0.001**
Color temperature×brightness	0.015	0.904	0.158	0.695	1.652	0.213	6.484	0.019*
Region×color temperature×brightness	0.102	0.903	1.322	0.274	0.210	0.680	4.816	0.023*

Degree of freedom=1, 21. * $p<0.05$, ** $p<0.01$

observed an interaction between color temperature and group at beta frequency ($F_{1,43}=4.508$, $p=0.050$). Post-hoc comparisons revealed that high color temperature enhanced the beta-band connectivity of young subjects ($p=0.007$), while not affecting that of elderly subjects ($p=0.979$) (Fig. 4B). As opposed to color temperature, brightness did not affect functional connectivity and there was no significant interaction between

brightness and group in all frequency bands (Table 3).

Subjective evaluations

There was a significant effect of color temperature on comfort ($F_{1,43}=7.302$, $p=0.010$), happiness ($F_{1,43}=4.361$, $p=0.043$), and refreshment ($F_{1,43}=4.166$, $p=0.047$). Subjects felt more refreshed in high temperature conditions while they reported

Table 3. Summary of repeated-measures analysis of variance for functional connectivity

Factors	Delta		Theta		Alpha		Beta	
	F	<i>p</i>	F	<i>p</i>	F	<i>p</i>	F	<i>p</i>
Color temperature	8.428	0.006**	2.842	0.099	3.242	0.079	4.207	0.046*
Color temperature×group	1.175	0.284	1.273	0.265	0.314	0.578	4.058	0.050
Brightness	2.031	0.161	0.023	0.881	0.508	0.480	0.272	0.605
Brightness×group	0.137	0.714	0.018	0.893	2.013	0.163	0.245	0.623
Color temperature×brightness	0.016	0.900	1.808	0.186	0.177	0.676	2.916	0.096
Color temperature×brightness×group	0.015	0.902	0.096	0.759	0.515	0.477	0.407	0.527
Group	2.258	0.140	0.281	0.599	0.225	0.637	2.171	0.148

Degree of freedom=1, 43. * $p<0.05$, ** $p<0.01$

Figure 5. Subjective feelings according to different light conditions. (A) Comfort. (B) Happiness. (C) Sleepiness. (D) Refreshment. Error bars indicate standard deviations. $n=45$. * $p<0.05$ for comparisons between high (6,500 K) and low (3,000 K) color temperature light; † $p<0.05$ for comparisons between bright (700 lx) and dark (300 lx) light. L-D: low-dark (3,000 K-300 lx), L-B: low-bright (3,000 K-700 lx), H-D: high-dark (6,500 K-300 lx), H-B: high-bright (6,500 K-700 lx).

more comfort and happiness in low temperature conditions (Fig. 5). A significant interaction between color temperature and group was not observed for all subjective feelings. In addition, we found a significant main effect of brightness ($F_{1,43}=9.929, p=0.003$) and interaction effect between brightness and group ($F_{1,43}=5.729, p=0.021$) on refreshment. Bright light provided more refreshing atmosphere than dark light. However, this effect was significant in young subjects ($p<0.001$) but not in elderly subjects ($p=0.591$). For subjective measures of sleepiness, there was no significant effect of color temperature or brightness. The results of repeated-measures ANOVA for subjective feelings are summarized in Supplementary Table 2 (in the online-only Data Supplement).

Discussion

The present study demonstrated that brain oscillations were influenced by brightness and color temperature of the LED light. Subjective feelings were also affected by the different lighting conditions, which was in agreement with previous studies.^{13,15} The consistent findings suggests that the lighting conditions and exposure protocols were appropriate in our experiments. Regarding power spectral density, the elderly subjects was mainly affected by brightness, whereas young subjects was influenced by color temperature of the LED light. In terms of the oscillation frequency, we found differential responses between the young and old age groups; elderly subjects showed changes in delta and theta power, whereas young subjects were characterized by changes in beta power. Furthermore, we found that resting-state functional connectivity was affected by color temperature but not by brightness. Exposure to high color temperature light increased functional connectivity in delta and beta frequencies. To the best of our knowledge, this is the first study to determine the lighting effect on functional connections in the brain. These results might help us to understand the neurophysiological effects of the light and to develop tailored lighting conditions for human health and disease.

Brain oscillatory activity changes with age, which is characterized by general slowing of background EEG activity together with decrement in amplitude and power of alpha rhythms.^{21,22} Furthermore, accumulating evidence have suggested that healthy aging is associated with a gradual decrease in delta and theta power.²³⁻²⁵ Of particular interest in our study is that bright light increased the frontal delta and theta power for elderly subjects, while not affecting spectral power of young subjects. Slow wave power of resting-state EEG was reported to correlate positively with cognitive performance such as verbal memory, attention, and executive function exclusively in healthy elderly adults.^{25,26} These findings indicate

that higher slow-frequency power is a neurophysiological marker of better cognitive function in healthy elderly subjects. Taken together with our observation, it is presumed that exposure to bright light in the elderly might facilitate brain activities related with cognitive processing. It is also supported by our result that enhancement of slow-frequency power under the bright light occurred in the frontal region. Previous studies have shown that frontal midline theta oscillations recorded in scalp EEG were generated by the anterior cingulate cortex, medial prefrontal cortex, and hippocampus.²⁷⁻²⁹ Furthermore, frontal theta oscillations are functionally implicated in cognitive operations, including working memory and episodic memory processes.^{30,31} These findings further support the hypothesis that the bright light in elderly subjects might contribute to enhancing brain activities associated with neurocognitive functions. However, an event-related potential study reported that the bright background light recued prestimulus alpha power and interrupted sustained attention performance.³² Moreover, the bright illumination decreased the prestimulus theta power in the frontal region during working memory tasks while not affecting cognitive performances.³³ These results are in contrast to our results. However, previous studies investigated brain oscillations during cognitive tasks in young participants, so that they cannot be directly compared to our findings derived from the resting-state EEG of elderly subjects. Further study is needed to understand the neurophysiological mechanisms and functional significance of age-dependent EEG responses to the bright illumination.

Another significant finding in this study was that color temperature conditions modulated resting-state functional connectivity. High color temperature light increased overall connectivity strength particularly in delta and beta frequencies. Physiological effects of color temperature on brain activity have been evaluated by recording EEG under different light conditions.^{13,14,34,35} The previous studies consistently concluded that high color temperature light enhanced arousal levels and brain activity compared with low color temperature light. Furthermore, results from subjective evaluation were in close agreement with EEG findings; subjective sleepiness was higher under low color temperature light while the level of concentration was higher under high color temperature condition.^{13,14,34,35} Deguchi and Sato postulated that the brain activating effect of higher color temperature light might be mediated by the ascending reticular activation system,³⁵ but physiological mechanisms remains unclear. From the viewpoint of functional connectivity, the present study provides a new insight into the effects of high color temperature light on brain activities. Functional networks for integrating separate brain regions are implicated in efficient cognitive abilities including attention.³⁶⁻³⁸ Moreover, functional connectivity

of resting-state networks was reported to significantly correlate with attention performance during cognitive tasks.^{39,40} Accordingly, these findings support the notion that enhanced functional connectivity by the high color temperature light might contribute to higher arousal and attention levels. In this regard, the high color temperature lighting could be helpful in environments requiring higher concentration and attention, such as office, laboratory, and school. Further studies using cognitively demanding tasks will be required to validate functional significance of hypersynchronization effect by high color temperature light.

There are several limitations in this study. Brain oscillatory characteristics shown in this study represented short-term responses to the light conditions with exposure time of five min. Therefore, long-term effects of the light conditions cannot be concluded from this study. Another limitation is that subjective feelings except for sleepiness were not measured by validated scales. Moreover, the interaction effects between light conditions and age groups appeared to be modest with marginal significance levels. The subtle differences between the different age groups might be attributed to relatively short exposure to the light. Another possible explanation is that the resting state was not the optimal condition to detect brain oscillatory responses to the different light. In addition, we detected the changes in resting-state brain oscillations without neuropsychological tests, so that we could not determine that the altered EEG activities have functional implications particularly in neurocognitive performances. Further research such as cognitive event-related potentials under different light conditions will be required to address these concerns.

Supplementary Materials

The online-only Data Supplement is available with this article at <https://doi.org/10.13078/jsm.17009>.

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