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Research Article

Effect of LED Lighting Illuminance and Correlated Color Temperature on Working Memory

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This study was conducted to verify how the illuminance and correlated color temperature of LED lighting affect working memory. For this study, an automatic LED lighting device based on a light sensor was developed and used, and the lighting conditions were treated with a total of six conditions (2 × 3): two illuminance conditions (dim: 400 lx, bright: 1,000 lx) and three correlated color temperature conditions (3,000 K, 5,000 K, and 7,000 K). There were 30 participants in the study, and the average age was 21.6 years (Standard deviation = 1.92). Participants were assigned to all six lighting conditions, and the placement order was randomized. For the measurement of working memory, 3-back task was used and the correct responses for 5 minutes were used as a dependent variable. As a result of repeated measures analysis of variance (ANOVA), both illuminance and correlated color temperature were found to be significant variables affecting working memory, and no interaction effect between illuminance and correlated color temperature was found. As a result of the post hoc verification conducted thereafter, the working memory performance in the bright light condition (1,000 lx) was 48.32 (Standard deviation = 15.63) on average, compared to 44.80 (Standard deviation = 15.29) in the relatively dim condition (400 lx). It was found that the condition of bright light was superior in performing working memory compared to relatively dim condition. The working memory performance in the correlated color temperature condition (5,000 K) was 48.32 (Standard deviation = 16.41) on average and higher than that of other color temperature conditions. As a result, working memory performance was the best in 1,000 lx, 5,000 K condition Mean = 53.43 (Standard deviation = 18.38), and 400 lx, 7,000 K condition Mean = 42.73 (Standard deviation = 17.68) showed the worst performance of working memory.

1. Introduction

Interest in the effects of light on humans has been accelerated by the advent of LED lighting. The reason is that LED lighting is easy to operate and can be easily applied to various scenes, making it suitable for light research. Moreover, as the well-being culture of modern people has spread, the desire to actively construct an optimal light environment, not just for lighting, has promoted light studies. Various light studies have reported that light affects human emotions, as well as arousal, sleep, fatigue, cognitive performance, and memory [1–5]. Particularly, memory is a very important topic in modern society. The reason is that memory is closely related to learning represented by education and dementia, one of the problems of modern society. Accordingly, many studies have focused on the relationship between light and memory, focusing on working memory [1, 3, 5].

The characteristics of light can be largely divided into studies conducted mainly on the illuminance of light, studies conducted on the color temperature and color of light, and studies that are not systematic, but consider the illuminance and color temperature of light together. Most studies dealing with intensity of illumination and working memory show that bright light is more effective in working memory than relatively dim light, but some studies have not found improvement in working memory in bright light or rather reported that the performance was reduced in bright light

[6–8]. For example, Huiberts et al. measured work memory through numerical width tasks at 200 lx and 1,000 lx illuminance in the morning and afternoon hours. As a result, in the easy task measured in the afternoon, bright light condition induces improvement of working memory. However, in the difficult task experiment conducted in the afternoon, contrary research results showed that bright light rather degrades performance [3]. In addition, a study by Smolders and de Kort, which studied the effects of light illuminance (200 lx vs. 1,000 lx) and fatigue on work memory showed that the correct response of the task was effective at relatively dim 200 lx [6].

On the other hand, studies dealing with the color temperature of light and working memory show more mixed results. Kenz verified the effect of the color temperature of lighting on free recall and problem solving. As a result, free recall was the best in the 3,000 K condition and relatively low and no significant difference was observed in the 4,000 K condition and the 5,500 K condition. And the problem-solving ability was also the best in the color temperature condition of 3,000 K and performed well in the order of 4,000 K condition and 5,500 K condition. They reported that the color temperature condition of 3,000 K had a superior performance difference than the other conditions [9]. In addition, Zhu et al. measured working memory under the conditions of 3,000 K and 6,500 K and found that the color temperature condition of 3,000 K performed better than the 6,500 K illumination [10]. However, in the study of the effect of color temperature on cognitive performance in the office environment conducted by Knez and Enmarker, no significant difference was found between 3,000 K (reddish) and 4,000 K (bluish) conditions [11]. Other studies have reported that color temperature conditions above 6,000 K are excellent for attention and working memory. Hawes et al. reported that performance of work memory such as symbol identification and color recognition task was the best at high color temperature conditions of 6,029 K [12]. And the study of Chellappa et al. showed that cognitive performance was the best under 6,500 K conditions [2].

As such, studies between color temperature and working memory to date report much more contradictory results than studies between illuminance and working memory. It can be presumed that the cause is due to the variety of experimental environments including lighting and working memory tasks. This is considered to be a phenomenon that occurs because studies between color temperature and working memory are still insufficient. In fact, there were many contradicting research results in the early days of the study of illuminance as well, but as more studies were conducted, it was proved in the direction that working memory was excellent in bright light conditions.

Although a minority, some studies have taken into account both illuminance and color temperature to explore the optimal lighting environment for working memory. Zhu et al. focused on two illuminance conditions (200 lx vs. 1,200 lx) and two color temperature conditions (3000 K vs. 6,500 K) to see how illuminance conditions affect working memory in the morning and during the daytime and verified it. As a result, it was found that the response of the cognitive performance task was the slowest at 200 lx and 6,500 K, and the accuracy of the cognitive performance task was higher in the bright lighting condition than in the dim lighting condition [10]. In addition, Ru et al. also evaluated cognitive performance under two illuminance conditions (100 lx vs. 1,000 lx) and two color temperature conditions (3,000 K vs. 6,500 K). In this study, the reaction velocity of the cognitive performance task was found to be excellent in the relatively bright condition of 1,000 lx. However, no statistical difference was found between the color temperature conditions [13].

However, most of the previous studies have been conducted in an excessively extreme lighting environment, and some studies have been designed for binominal experiments such as bright and dim light, cool color temperature, and warm color temperature. Binomial experimental design can verify the effect of light on memory, but there is a limitation that the binomial experimental design cannot be explained with respect to detailed aspects. In addition, many studies have verified the effectiveness of working memory through independent conditions of illuminance or color temperature. Although some studies have considered the illuminance and color temperature together, the number is very small, and the results are very mixed. Since both the light illuminance and the color temperature are variables that can affect memory, it is possible to search for an optimal lighting environment for working memory only when the illuminance and color temperature are considered together. Therefore, this study was conducted to systematically verify the effect of light on working memory through a more continuous experimental design while considering the illuminance and color temperature together with the focus on LED lighting. Besides, this study seeks to explore and propose the optimal lighting environment for working memory applicable to real life.

2. Materials and Methods

2.1. Participants. There were 30 experiment participants, 19 men and 11 women, and the average age was 21.6 years (SD = 1.92). Prior to the experiment, the orientation and task implementation method throughout the experiment were explained, and the tasks to be performed in order to improve the adaptability of the experiment were preliminarily conducted. Through this, the participants' cognitive impairment and the suitability of the participation were verified.

In addition, the following measures were taken to control other variables that may affect the experiment participants and to ensure consistent condition of the participants. Priorly, before the participants participated in the experiment, we received a pledge from the participants. The contents of the pledge included an explanation of the cost of participating in the experiment, as well as the content of getting enough sleep and refraining from drinking alcohol or caffeine if possible. The cost of participating in the experiment was quite incentive from the participant's point of view, and it was said that if the participant violated the request or did not actively perform the experiment, the experimental participation cost was not paid. Through this, efforts were made to strictly control the participation of experimental participants.

And we asked about the condition of the participants verbally before the experiment. It was checked whether there was any situation in violation of the request, including sleep, and whether the current participant's subjective condition was in a state sufficient for the experiment.

2.2. Experiment Environment. For this experiment, an automatic LED lighting device based on a light sensor and a lighting control system developed to construct a systematic lighting environment were developed and used. The structure of the automatic lighting device consists of a power switch, a power connection jack, a sensor part, an inner heat sink, a light diffuser plate, and an attached briquette as shown in Figure 1. And a color temperature sensor and an illuminance sensor were attached to the sensor portion as shown in the figure at the corner of the lighting. The input power of this device is 24VDC, and the high-power LED was used as the light source. The light power is approximately 10–20 W, and the LED Mounting Type is equipped with a separate steel bracket. The case material was made of aluminum, and the operating temperature was designed to be operated at $-10^{\circ}\mathrm{C} \sim 70^{\circ}\mathrm{C}$. The automatic lighting device is equipped with 2.4 GHz Wireless, so it can be controlled in both PC and mobile environments. In addition, the standard of the automatic lighting device is $700 \times 60 \times 45$ (mm). The lighting was in the form of a stand and was used in the form of local lighting to illuminate the surface of the desk. The illumination conditions were treated with two illuminance conditions (400 lx dim light vs. 1,000 lx bright light) and three correlated color temperature conditions (3,000 K, 5,000 K, and 7,000 K). The spectral power distribution according to the correlated color temperature is shown in Figure 2. An experiment environment such as Figure 3 was formed for this study. In the lab, light from other sources was blocked using a light-blocking curtain. The experimental laboratory temperature was maintained at $24^{\circ}\mathrm{C} \pm 4^{\circ}\mathrm{C}$ and $50\% \pm 10\%$ humidity to meet PMV conditions of ASHRAE standards. In addition, lighting conditions were treated based on the identification mark (+) marked in the middle of the desk as shown in Figure 3.

2.3. Work Memory Measurement Tool. Working memory was measured through the n-back test, one of the number-wide tasks. The n-back task is often used in psychology and cognitive neuroscience as a task to measure work memory or a part of work memory, first introduced by Kirchner [14]. The n-back task is a task for determining whether a continuous stimulus is given and the current stimulus matches the previous n-th order stimulus. As n of the n-back task increases, the task difficulty increases, and the difficulty of the task is adjusted through n. In this experiment, working memory was evaluated through 3-back task.

2.4. Experiment Procedure. In this study, through the repeated measure experiment design, all participants participated in all six experimental conditions (A condition: 400 lx, 3,000 K, B condition: 400 lx, 5,000 K, C condition: 400 lx, 7,000 K, D condition: 1,000 lx, 3,000 K, E condition: 1,000 lx, 5,000 K, F condition: 1,000 lx, 7,000 K) allocated randomly. First, the participants adapted to the lighting environment through 2 minutes of dark adaptation and 2 minutes of light adaptation. Subsequently, 3-back task was performed for 5 minutes, and the number of correct answer responses among the 3-back tasks was used as a dependent variable.

This experiment was conducted only for 4 hours from 2 pm to 6 pm in consideration of postprandial drowsiness, etc. In order to minimize the interference of the previous experiment, the test participants were assigned to only one experimental condition per day.

2.5. Statistical Analysis Method. Descriptive statistics were calculated for all the variables. Then, to analyze the effect of illuminance and color temperature on working memory, repeated measures analysis of variance(ANOVA) was performed on two illuminance conditions and three color temperatures. Also, the difference in working memory according to the six lighting conditions was performed through a single level of repeated measures analysis of variance (ANOVA). Post hoc analysis was performed using the least significant difference (LSD) method. Significance was defined as $p < 0.05$.

3. Result and Discussion

As a result of descriptive statistical analysis of working memory according to illuminance and correlated color temperature, as shown in Table 1, the average number of correct responses was 53.4 (Standard deviation = 18.38) under 1,000 lx and 5,000 K lighting conditions, indicating that the performance of working memory was the best. On the other hand, at 400 lx and 7,000 K, the average performance was 42.73 (Standard deviation = 17.68), indicating that the performance of working memory was the lowest.

Repeated measures analysis of variance (ANOVA) was performed to analyze the effect of the illuminance and correlated color temperature of LED lighting on working memory. As a result of variance analysis, both the illuminance ($F = 5.36$, $p < 0.03$) and the correlated color temperature ($F = 7.34$, $p < 0.00$), as shown in Table 2, were found to be significant variables affecting working memory at 95% confidence level. However, there was no interaction effect between illuminance and color temperature.

Subsequently, difference verification was performed through the least significant difference (LSD) method to analyze the difference between each condition of illuminance and correlated color temperature on working memory. As a result of analysis, the illuminance of working memory was found to be significantly better than 1,000 lx

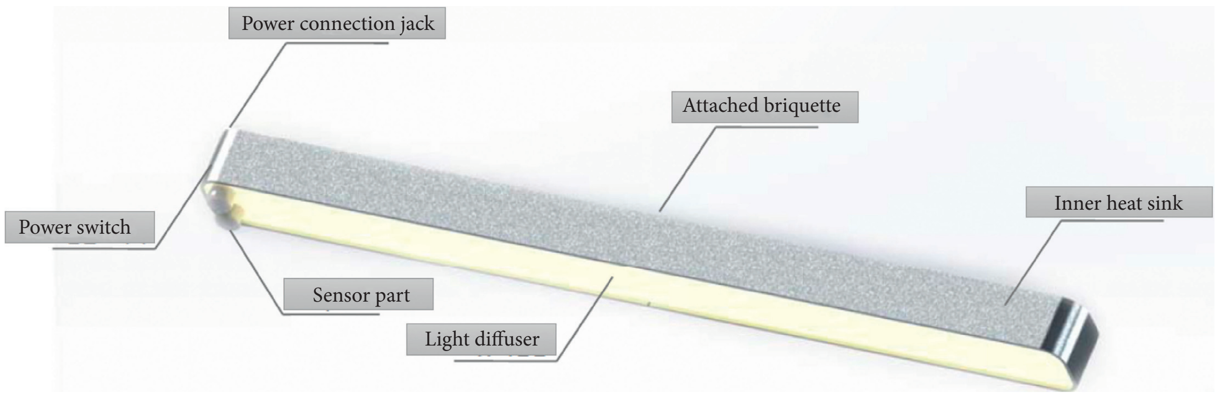

Figure 1: Automatic LED lighting device based on light sensors.

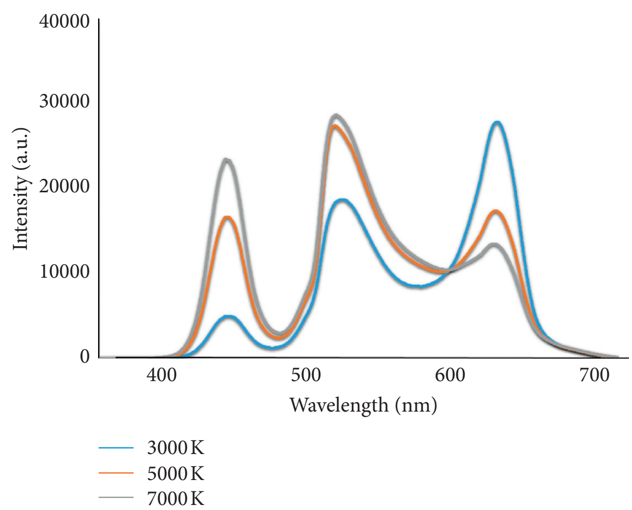

Figure 2: Spectral power distribution.

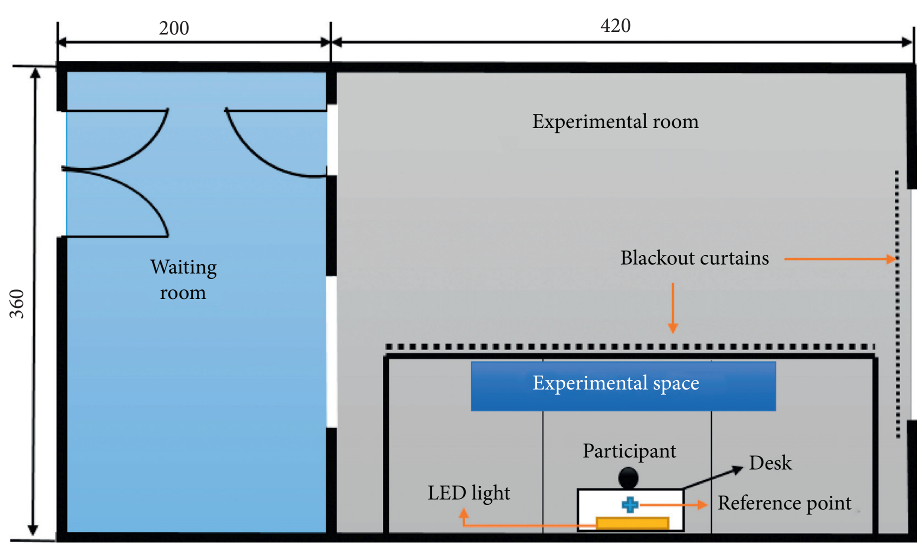

Figure 3: Experimental laboratory.

Table 1: Descriptive statistics of working memory according to light illuminance and correlated color temperature (CCT).

Illuminance CCT	400 lx		1,000 lx		Total		*N*
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	
3,000 K	43.70	17.00	45.73	18.77	44.72	16.24	30
5,000 K	48.97	18.51	53.43	18.38	50.70	16.41	30
7,000 K	42.73	17.68	45.80	17.73	44.27	15.40	30
Total	44.80	15.29	48.32	15.63			

Table 2: Analysis of the effect of illuminance and correlated color temperature (CCT) on working memory.

	Sum of square	Degree of freedom	Mean square	F	p
Illuminance	558.27	1	558.27	5.36	0.03*
CCT	1547.81	2	773.91	7.34	0.00**
Illuminance*color temperature	93.08	2	45.54	0.31	0.74

$^{*}p < 0.05$, $^{**}p < 0.01$.

Table 3: Difference verification of illuminance on working memory.

	Mean difference (I-J)	Standard error	p
1,000 lx (I) vs. 400 lx (J)	3.52	1.52	0.03*

$^{*}p < 0.05$, $^{**}p < 0.01$.

Table 4: Difference verification of correlated color temperature on working memory.

	Mean difference (I-J)	Standard error	p
5,000 K(I) vs. 3,000 K(J)	5.98	1.74	0.00**
5,000 K(I) vs. 7,000 K(J)	6.43	1.76	0.00**
3,000 K(I) vs. 7,000 K(J)	0.45	2.10	0.83

$^{*}p < 0.05$, $^{**}p < 0.01$.

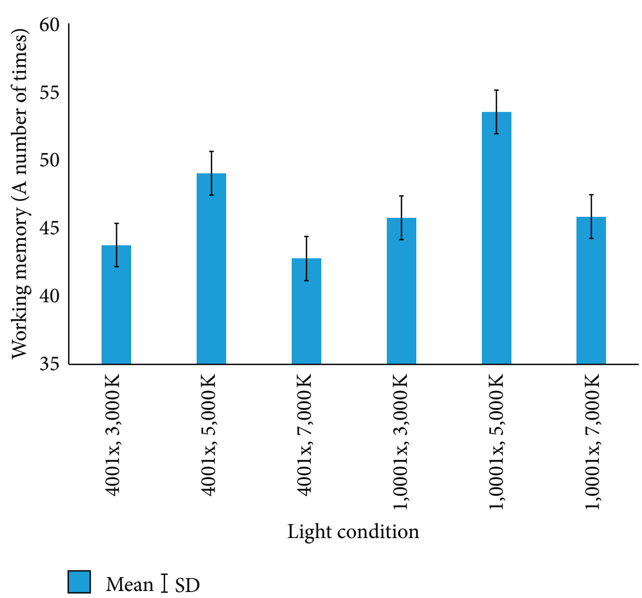

Figure 4: Difference in working memory according to light illuminance and color temperature condition.

condition ($M = 48.32$, $SD = 2.85$) than 400 lx condition ($M = 44.80$, $SD = 2.80$) as shown in Table 3. These results can be said to support previous studies of excellent working memory in relatively bright light.

And, after the correlated color temperature difference verification, it was found that there is a statistically significant difference between 3,000 K condition (Mean = 44.72, Standard deviation = 2.97) and 5,000 K condition

(Mean = 50.7, Standard deviation = 3.0), 5,000 K condition and 7,000 K condition (Mean = 44.27, Standard deviation = 2.81), and the 5,000 K condition had the most positive effect on working memory performance as shown in Table 4.

In summary, 1,000 lx (5,000 K) condition was the best for performing working memory according to the illuminance and the correlated color temperature as shown in Figure 4. In the order of 400 lx (5,000 K) condition, 1,000 lx (3,000 K), and 1,000 lx (7,000 K) conditions, it was found to be an excellent lighting environment for working memory. On the other hand, the condition of 400 lx (7,000 K) was the worst lighting environment for working memory.

Through this study, it was found that the working memory is the best in the condition of relatively bright 1,000 lx in illuminance and the best in the 5,000 K condition in color temperature. These results support the previous studies that working memory is excellent in bright light. However, in terms of color temperature, it can be said that the result is inconsistent with the previous study that showed that working memory was excellent at about 3,000 K or 4,000 K, or above 6,000 K. In addition, in this study, working memory was found to be the worst under a color temperature of 7,000 K. This seems to need to be repeatedly verified through more systematic research.

And through this experiment, the best LED lighting condition for working memory was found to be 1,000 lx (5,000 K).

4. Conclusion

This study was conducted to verify the effect of illuminance and correlated color temperature on working memory and to explore the optimal lighting environment that can activate working memory. As a result of the study, both the illuminance and the correlated color temperature were significant variables affecting working memory, and among the lighting environments used in the experiment, a lighting condition of 1,000 lx (5,000 K) was found to be the best lighting for working memory. The more specific results are as follows.

First, through this study, it was verified that the performance of working memory is excellent in a relatively light condition. These results can be said to support previous studies of excellent working memory at high illuminance.

Second, in this study, the 5,000 K condition was found to have a positive effect on working memory in correlated color temperature.

Finally, through this study, the 1,000 lx (5,000 K) lighting environment was found to be a better lighting condition for working memory than other conditions. Of course, the lighting conditions used in this study still have limitations to represent all lighting. However, this study is significant in that it explores the working memory performance by considering the illuminance and color temperature together and suggests a standard for a lighting environment that can be maximized in the working memory.

Despite these findings, this study still has a limitation in not considering various variables that can affect working memory due to experimental conditions. First, this experiment did not consider temporal variables like morning and afternoon. As shown in the study of Huiberts et al. [3], there is a possibility that the performance of tasks in the morning and afternoon affects working memory. However, in this study, the experiment was conducted only in the afternoon hours from 2 o'clock to 6 o'clock. It is necessary to clarify how illuminance and difference in color temperature affect working memory in the morning and afternoon through future research. Second, the participants of this experiment were mainly college students in their early twenties. Memories are clearly different depending on the age group, such as young people and the elderly, and there is a good possibility that the effects of illumination and color temperature are also different. In future studies, it is judged that there is a need to organize a more systematic experiment for experiment participants of a wider range of ages. Finally, in future studies, it is considered that there is a need to further strengthen the control over the experiment in the laboratory environment and experiment participants. Although not considered in this study, if the amount of Co_2 in the laboratory and the stress measurement of the experimental participant are included, it is considered that a more systematic study could be achieved.

Data Availability

The data used to support the findings of this study are included within the supplementary information file.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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Supplementary Materials

This data are the result of working memory measured under each lighting condition through experiments. The working memory was measured through 3-back task, and it is the number that responded correctly for 5 minutes. (*Supplementary Materials*)

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