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Research Article
The Influence of LED Lighting on Attention and Long-Term Memory

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The fact that the illuminance of LED lights affects human attention and long-term memory has been verified through various studies, but there are no consistent research results about what level of illuminance is effective. The aims of this study were to systematically verify the effects of LED lighting on attention and long-term memory. The experiment was designed with four illuminance levels—300 lx, 400 lx, 500 lx, and 1,000 lx—as experimental conditions to determine the effects of LED lights on attention and long-term memory. Participants in the experiment were 18 college students. The attention task was performed using a handmade attention measuring instrument. Long-term memory was measured by the word fragment completion (hereinafter, referred to as "WFC") task on the memory retention volume of the learning task that was learned exactly 24 hours before. Of the total 20 tasks, the ratio of correctly retrieval tasks was used as a dependent variable. As a result, attention showed the highest performance with a mean performance of 19.39 (SD = 3.78) at 1,000 lx. A statistically significant difference was also found between the 1,000 lx and 300 lx conditions ($p = 0.01$). On the contrary, long-term memory showed the highest retrieval rate at an average of 58.06% (SD = 22.57) at 400 lx, and long-term memory performance was better in the order of 500 lx (mean = 48.89, SD = 20.33), 1,000 lx (mean = 45.83, SD = 23.53), and 300 lx (Mean = 43.33, SD = 19.10). Statistically, there was a significant difference between 300 lx and 400 lx ($p = 0.01$), 400 lx and 1,000 lx ($p = 0.01$). Through this study, it was verified that the effects of attention and long-term memory are different according to the illuminance of LED lighting, and these results can be important data to clarify the influence of light on human memory in the future.

1. Introduction

Light affects the 24-h circadian rhythm and is accepted as the main cause of activity and acute alerting [1, 2]. In particular, the illumination of light has been reported to affect cognitive functions such as attention, working memory, and long-term memory [3–8]. However, research findings on the effects of light have not always been consistent. Though some studies have suggested that a relatively bright light produces psychological alertness and that the effect leads to improved attention and cognitive performance, other studies have failed to find improved cognitive performance or have even found lower performance in the bright light condition [9–11]. For example, in the study by Kretschmer et al. [12],

the correct response performance of the working memory task was statistically much better in the bright condition (3,000 lx) than in the dim condition (300 lx), but the false response performance did not show a significant difference in both conditions. And, sustained attention did not show any significant difference in both bright light and dim light conditions [12]. This inconsistent aspect of the light effect can cause a lot of confusion in the use of light in real scenes.

One of the reasons for the inconsistency between the results of illuminance and cognitive performance is that the illuminance conditions are often designed by binominal approach of bright light vs. dim light. This type of comparison is bound to have a clear limit to determine the effect of light on cognitive performance. This is because the result

may vary depending on how "bright light" is defined. For example, Campbell and Dawson [13] studied the effect of ambient light on alertness and cognitive performance in night workers and set the three illuminance conditions of 10~20 lx, 100 lx, and 1,000 lx as experimental conditions. As a result, they reported that participants exposed to ambient light of 1,000 lx were significantly improved in alertness and cognitive performance compared to other conditions [13]. Similarly, in the study by Badia et al. [6], they measured alertness and behavior task performance for night workers and reported that bright light was effective in improving alertness and performance [3]. However, the experimental illuminance conditions were set to bright condition (5,000 lx) and dim condition (50 lx), unlike the condition of Campbell and Dawson [13]. In this experiment, the illuminance difference between dim condition and bright condition was 4950 lx. The experimental results of both studies were similar, but there was a significant difference between the bright and dim light they defined. In the abovementioned study by Kretschmer et al. [12], the bright illuminance condition and the dim illuminance condition were 3,000 lx and 300 lx, respectively. The dim illuminance condition defined in this study, 300 lx, was applied to the study by Campbell and Dawson [13], but was it really a dim illumination condition? Of course, the above studies may be meaningful in that they searched that bright light conditions have a positive aspect to alertness and cognitive performance compared to dim conditions, but there clearly was a limit in drawing conclusions as to which illuminance has a positive effect on the actual scene. This is because it is not possible to completely exclude the presence of other illuminance conditions that are excellent in alertness and cognitive performance, and that bright and dark conditions are relative rather than absolute.

Therefore, the study to explore the effects of light illuminance requires a more continuous approach than a binominal approach such as bright light conditions and dim light conditions.

In addition, previous studies on the relationship between light illuminance and cognitive performance focused mainly on working memory, including arousal and attention. But memory does not just mean working memory. According to the multistore model by Atkinson and Shiffrin [14], memory can be divided into sensory memory, short-term memory or working memory, and long-term memory [14].

Long-term memory is a large-capacity repository with no capacity limitations compared to sensory or working memory and can store information for a longer period of time than other memory repositories. The rehearsal information from the working memory is transferred to the long-term memory; the necessary information can be obtained from the working memory retrieved from the long-term storage, and cognitive performance is achieved. In general, the term "remember" which is commonly used in daily life means most of the long-term memory. However, most of the studies between light and memory focus on attention and working memory.

Many studies have been conducted on the effect of light on working memory. The central aspect of working memory is attention, which affects all major processes in memory. As mentioned earlier, many studies on attention and working memory have suggested that working memory is activated at a relatively high illuminance. However, little research has been done as to whether the high illuminance of light is good for the long-term memory. The study by Jung et al. [8] would be the only one that has studied the relationship between light illuminance and long-term memory. They experimented with the superiority of long-term memory at 400 lx, 700 lx, and 1,000 lx using LED lighting. As a result, they claimed that long-term memory was best at 400 lx, a relatively dim condition, unlike working memory [8]. However, their research has not been repeatedly validated by other studies, and there is a limit because long-term memory measurements were made after too short a time (after 5 minutes) after the task was performed. Spaces that are too short after task performance can obscure the boundaries between working memory and long-term memory.

Thus, this study was performed to systematically verify the differences between attention and long-term memory aspects by supplementing the limitations of previous studies. Under this objective, first, the study reverified the previous studies and designed the experiment using a greater spectrum of illuminance than the bright-dim binominal design to determine the optimal illuminance to use in real-life settings. Specifically, the study used 300 lx, 400 lx, 500 lx, and 1000 lx as experimental conditions. These experimental conditions were distributed around 400 lx, the most effective condition for long-term memory according to Jung et al. [8]. Second, in the study, long-term memory was measured 24 hours after the learning task to clearly distinguish long-term memory from working memory and empirically verify the effects of light on long-term memory. Finally, the study included measurements of both attention and long-term memory to gain clear understanding of the performance difference between attention and long-term memory according to illuminance.

2. Materials and Methods

2.1. Participants. The experiment was conducted with 18 adults (5 men and 13 women) with no cognitive impairment and a mean age of 23.3 (SD = 1.14). The recruitment of the experiment participants was done through K University's online bulletin board, and the participants were all students at the university. The recruited experiment participants were given orientation to explain the experiment schedule and method, and only those who successfully performed the task by performing a simple experiment task were selected as the experiment participants. Participants were asked to consume no alcohol or caffeine and to get enough sleep prior to the experiment to prevent negative effects on cognitive performance, and only the participants who agreed to the requirements signed the consent form and participated in the experiment.

2.2. Experiment Environment. The experiment was designed with four illuminance levels (300 lx, 400 lx, 500 lx, and

(a)   (b)

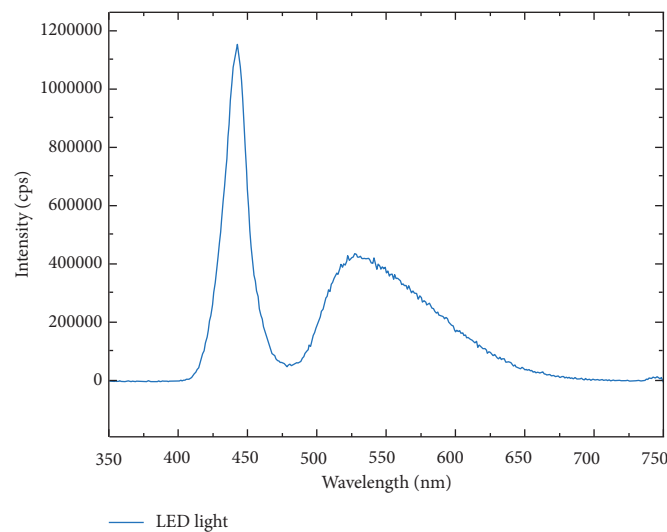FIGURE 1: LED light (GM10743).

FIGURE 2: Spectral power distribution.

1000 lx) as experimental conditions to determine the effects of LED lights on attention and long-term memory. The color temperature was 5500 K for all four conditions, which were the same for all variables except the illuminance level. The lighting used in the experiment is a GM10743 model manufactured by Ningbo Golmore Industries, as shown in Figure 1. The product was 9 cm in diameter and contained 5 small LED bulbs. Illuminance was manipulated using 12 lights. In addition, the spectral power distribution of the light used in the experiment 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 $24°C \pm 4°C$ and $50\% \pm 10\%$ humidity to meet PMV conditions of ASHRAE standards.

2.3. Attention Measurement. A response measuring device was prepared and used to measure attention. The device consists of 10 symbols (e.g., ∧, ⊂, and Z) and 10 corresponding keys as shown in Figure 4; a user pressed the keys

that corresponded to consecutively displayed symbols. The device was set up in such a way that if the user tried to press a button that did not match the displayed symbol, the button could not be pressed down, and the display did not move to the next symbol. In other words, a user had to press the correct button to proceed to the next symbol. The performance of attention task was measured by counting the number of symbols for which the user pressed the correct keys for a minute.

2.4. Long-Term Memory Measurement. Long-term memory was measured by using the WFC task. WFC is a method of measuring long-term memory indirectly by completing the nonsense syllable already learned [15–17]. This study refers to previous studies that applied the WFC task to long-term memory and measured it in accordance with long-term memory. The nonsense syllable task was to learn 20 items per one illuminance condition; 5 items of 4 words, 5 items of 5 words, 5 items of 6 words, and 5 items of 7 words were constructed to minimize the effect of difficulty. Participants learned the nonsensical words and performed the WFC task
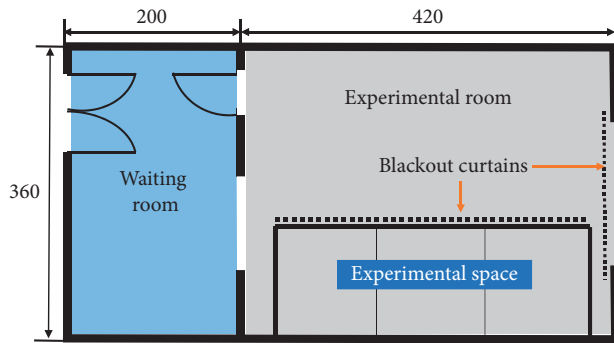
FIGURE 3: Interior structure of experimental laboratory.

FIGURE 4: Attention measuring device.

FIGURE 5: Experimental procedure.

TABLE 1: Descriptive statistics of attention and long-term memory according to illuminance of LED lighting.

Illuminance levels (lux) (lx)	Attention (a number of times)		Long-term memory (%)		N
	Mean	SD	Mean	SD	
300	16.22	3.78	43.33	19.10	18
400	17.50	5.54	58.06	22.57	18
500	18.00	5.18	48.89	20.33	18
1000	19.39	5.42	45.83	23.53	18

TABLE 2: ANOVA results of attention and long-term memory according to illuminance of LED lighting.

	DF	SS	MS	F	p
Attention	3	92.56	30.85	3.39	0.025*
Long-term memory	3	2234.72	744.91	3.21	0.031*

* $p < 0.05$.

in precisely 24 hours by completing two blank letters in each word (e.g., _ff_ and ry_d_). The performance of the long-term memory task was measured by obtaining the proportion of the correctly completed words out of the twenty words.

2.5. Experiment Procedure.

In this study, all participants were randomly allocated to all four conditions of 300 lx, 400 lx, 500 lx, and 1,000 lx through a repetitive measurement experiment design. Prior to each learning task per condition, participants underwent the two-minute dark and light adaptation periods, respectively. Over the next 10 minutes, participants learned about 20 nonsense syllables. After 10 minutes of the learning, the participants soon completed the working memory task. In the attention task, where performance was measured using a cognitive response measuring device, the number of correctly responded symbols in one minute was counted for use as a dependent variable. Subsequently, the participants returned to the experimental laboratory exactly 24 hours later and performed a long-term memory task of 20 items based on previous learning. The long-term memory was measured using the WFC task, and the proportion of the correctly recognized items out of the 20 items was obtained for use as a dependent variable. The specific experimental procedure is shown in Figure 5.

2.6. Statistical Analysis Method.

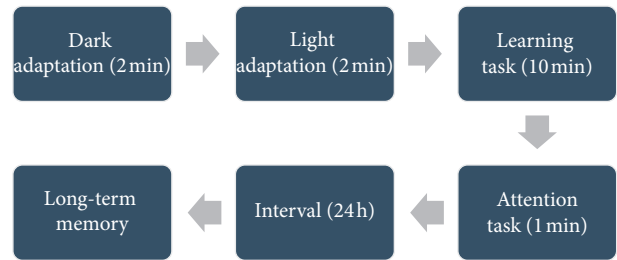Descriptive statistics were calculated for all the variables. Difference verification between attention and long-term memory according to the illuminance of LED lighting was made through a repeated measure ANOVA through SPSS 20.0 (SPSS Inc., Chicago, IL, USA). Post hoc analysis was performed using the LSD method. Significance was defined as $p < 0.05$.

3. Result and Discussion

The descriptive statistics of attention and long-term memory according to illuminance conditions are shown in Table 1. The mean score for attention was the highest (at 19.39) in the 1000 lx condition and the lowest (at 16.22) in the 300 lx. However, the mean recognition rate for long-term memory was the highest (at 58.06%) in the 400 lx condition and the lowest (at 43.33%) in the 300 lx condition.

ANOVA was performed to verify whether the attention and long-term memory were significantly different according to the illuminance level. As shown in Table 2, the experimental results showed that there was a statistically significant difference at 95% confidence level in both attention ($F = 3.39$, $p = 0.025$) and long-term memory ($F = 3.21$, $p = 0.031$).

After this, the post hoc test was conducted to specifically find out the difference according to the illuminance level. The test results showed that there was a statistically significant difference in attention between 300 lx and 1000 lx conditions (mean difference = −3.17, $p = 0.012$). The result
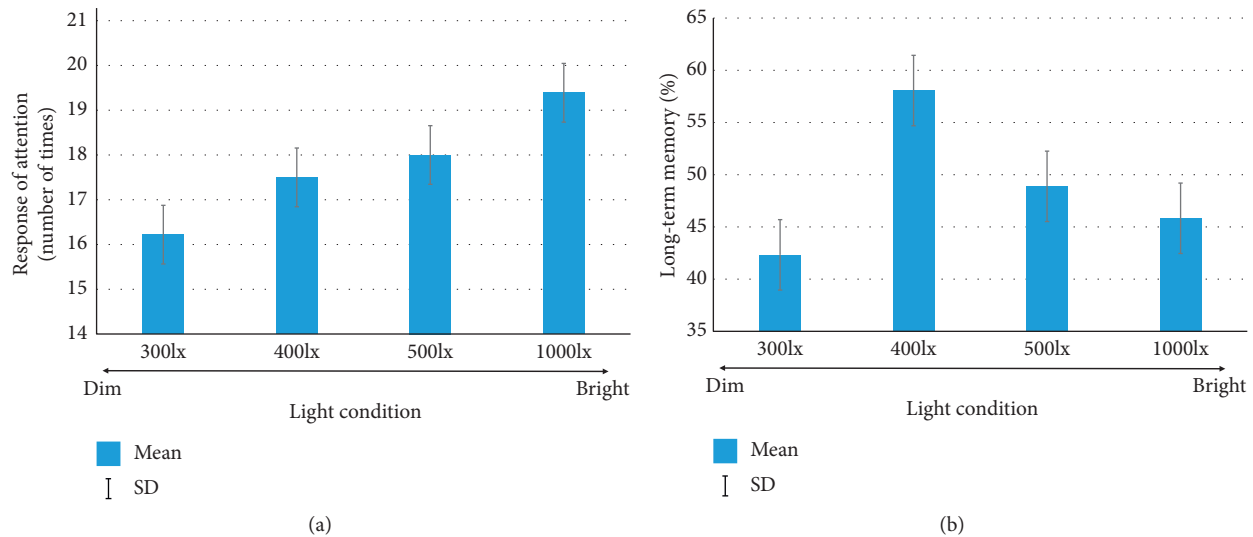
FIGURE 6: Difference between attention (a) and long-term memory (b) according to illuminance of LED lighting.

suggests that attention functions the best in the relatively high illuminance level of the 1000 lx condition and the worst in the lowest level of the 300 lx. This result is consistent with the studies by Smolder and Smolder [9] and Rüger et al. [11] that attention is excellent under bright light conditions.

On the other hand, the post hoc analysis results of long-term memory showed statistically significant differences between the 300 lx condition and the 400 lx condition (mean difference = –14.72, $p = 0.014$) and between the 400 lx condition and the 1000 lx condition (mean difference = 12.22, $p = 0.011$). The result suggests that the recognition rate for long-term memory is the best at 400 lx, followed by the order of 500 lx, 1000 lx, and 300 lx. This result is consistent with a study by Jung et al. [8] that long-term memory is superior in 400 lx relatively dim condition.

In summary, as shown in Figure 6, attention tended to be linearly activated as the illuminance increased, whereas long-term memory showed the lowest performance at 300 lx, the highest performance at 400 lx, and the inverted U shape, which progressively decreased performance.

4. Conclusion

The purpose of this study was to supplement the limitations of the existing studies, to reverify the existing studies' results that the long-term memory was the best at 400 lx, and to find out the optimal illuminance level at the same time. In addition, the study showed that long-term memory performed the best at 400 lx when compared with 300 lx, 500 lx, and 1,000 lx conditions. These results support Jung et al.'s [8] finding that working memory is excellent at 400 lx. Retrieval of long-term memory was the lowest at 300 lx and then steeply inclined to 400 lx, followed by a gradual decline as illuminance further increased. And the attention showed the lowest performance at 300 lx, which is the darkest condition in this experiment, and the attention was also linearly activated as the illuminance became bright. These results support previous studies that have previously addressed the relationship between light and attention. However, the fact that attention is excellent in bright light does not mean that bright light conditions are always good for cognitive performance. In this experiment, long-term memory retrieval was the best at 400 lx apart from light and darkness of light. Rather, the long-term memory retrieval at 1,000 lx condition, which is the best condition for the performance of attention, was not significantly better than the 400 lx condition. These results suggest that the optimized illuminance for memory should be considered separately from attention and long-term memory. Attention is activated as the light becomes brighter, but long-term memory is the most active near 400 lx. And, it can be concluded that 300 lx illuminance condition in attention and long-term memory is the worst condition because this illuminance shows the poorest performance and retrieval. In addition, this study can provide an issue that attention and long-term memory may differ in the active process. This is because the attention and long-term memory are activated differently according to the illuminance of the LED lighting. This should be verified through further studies.

This study is meaningful in that it clarified the difference by verifying the effect of illuminance, especially LED lighting, on attention and long-term memory more clearly and systematically. In addition, this study is significant in that it suggested optimized illuminance of attention and long-term memory; attention is the best at 1000 lx, a relatively bright light condition, and long-term memory is the best at 400 lx condition.

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

Supplementary Materials

Attention and long-term memory data for each illuminance condition. Attention is the number of successful attention tasks in one minute, and long-term memory is the percentage of successful retrieval tasks. (*Supplementary Materials*)

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