Dynamic lighting system for the learning environment: performance of elementary students

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Abstract: This study aims to investigate the effects of lighting color temperatures on elementary students' performance, and thereby propose a dynamic lighting system for a smart learning environment. Three empirical studies were conducted: First, physiological responses were measured as a potential mediator of performance. Second, cognitive and behavioral responses were observed during academic and recess activities. Lastly, the experiment was carried out in a real-life setting with prolonged exposure. With a comprehensive analysis of the three studies, three lighting presets–3500 K, 5000 K, and 6500 K–are suggested for easy, standard, and intensive activity, respectively. The study is expected to act as a good stepping stone for developing dynamic lighting systems to support students' performance in learning environments.

OCIS codes: (230.3670) Light-emitting diodes; (330.1690) Color; (330.5020) Perception psychology.

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1. Introduction

Over the past few years, solid-state lighting has been emerging as a next-generation lighting technology. Solid-state lighting sources such as light-emitting diodes (LEDs) have become particularly popular because they are highly efficient, physically small, long-lasting, energy saving, and environmentally friendly [1]. Another aspect of solid-state lighting that is important to many end users is a real-time tunable spectrum [2, 3]. Recent studies asserted that lighting with different correlated color temperatures (CCTs) has profound effects on both the physical and mental conditions of humans [4–8]. In support of these arguments, researches have shown that lighting can influence human physiology, such as heart rate, blood pressure, and brainwaves [7, 8]. In addition to physiological effects, variable lighting CCTs exert a potential advantage indoors with respect to psychological state [4, 6].

Besides the physiological and psychological effects of lighting, studies have also indicated positive effects of specific lighting conditions on behavior, such as working speed, productivity, and accuracy. However, such empirical studies have mainly focused on commercial [9] and working environments [10, 11], and studies on learning environments are still very limited. Knez [12] revealed that high school students performed better in warm than in cool white lighting, which is contradictory to the general findings indicated in working environments. A more recent study, however, indicated that using high-CCT white lighting can improve subjective alertness in students attending lectures [13]. To further highlight the potential of using a tunable light source to improve everyday life, some researchers have expanded their scope of research from static lighting to dynamic lighting in learning environments. Dynamic lighting refers to lighting that provides varying lighting parameters that vary over time to support user activities [14, 15]. In one of the earliest studies of dynamic lighting, Wessolowski [16] recorded significant improvements in German students' performance as assessed by increased reading speed, decreased errors, and decreased hyperactive behavior. In support of this argument, Sleegers, et al. [15] observed a positive effect of dynamic lighting on the concentration of Dutch elementary students. Although these studies did find positive effects of dynamic lighting, Izsó [14] has disputed these effects.

The inconsistent findings of earlier studies indicate that the effect of lighting on students' performance is in part dependent on the research design. Previous studies have varied greatly in terms of target participants, lighting parameters, duration, and measurements. Hence, more research is needed to understand the effect of lighting in learning environments to provide unequivocal experimental evidence. As such, this paper builds on and extends previous studies by conducting a series of three different and complementary empirical studies on the effects of different lighting CCTs on elementary students' performance, namely physiological, cognitive, and behavioral aspects. By doing so, this study aims to propose a dynamic lighting system that could be applied as the basis for designing a user-centered lighting control system for a smart learning environment.

2. Preliminary study

2.1 Method

The purpose of the preliminary study was to investigate the effect of different lighting CCTs on physiological response, as a potential mediator of performance. An electrocardiogram (ECG) was recorded as a non-invasive measurement of each participant's level of arousal. A total of seventeen healthy participants (ten males and seven females) were recruited. For an accurate data measurement, adults were recruited instead of children, as ECG signals are strongly affected by motion artifacts. The average age of the participants was 24.47 years, with a standard deviation of 4.00 years. They were not under any medication that might affect their neural activities. All participants were paid volunteers. Prior to the experiment, all participants were tested for color detection deficiencies using the Ishihara Test for Color Blindness. Ethical approval was obtained prior to the commencement of all studies concerning human participants.

The study was conducted in a room equipped with an LED luminous ceiling, as shown in Fig. 1. The CCTs of ambient lighting could be controlled by adjusting the *R*, *G*, *B*, and *W* (White) input values. As for the lighting stimuli, three CCTs were selected: 3500 K, 5000 K, and 6500 K. The illuminance level was adjusted to approximately 500 to 600 lux, which is a recommended illuminance for tasks with medium visual requirements [17]. All curtains were closed to block off the fluctuation of natural daylight. The colorimetric values of each stimulus were measured on a horizontal plane at the participants' desk level with a chroma meter (Konica Minolta CL-200), as shown in Table 1. The room was refurbished to appear like a classroom, and the walls and majority of the furniture were white. The ambient conditions of the room were maintained for human comfort [18]: ambient temperature = 23.8 ± 2 °C; ambient humidity = 39 ± 5%; and ambient noise = 44.6 ± 10 dB(A).

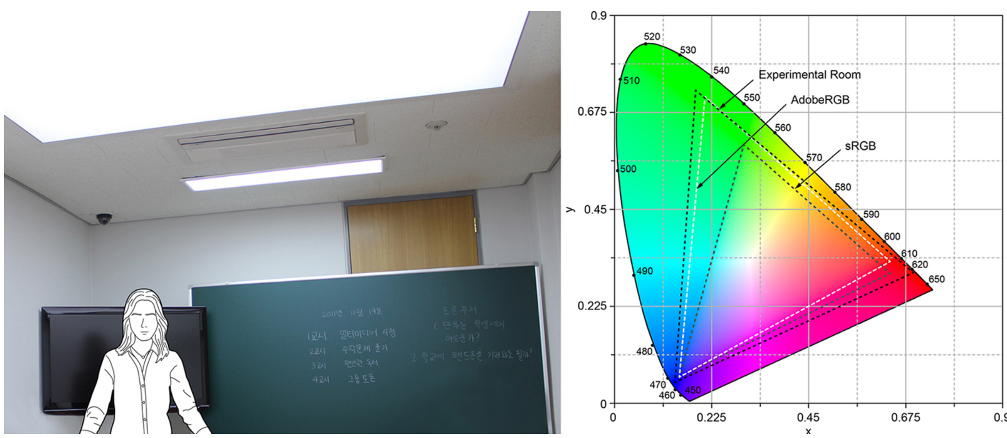

Fig. 1. The LED luminous ceiling of the experimental room (left) that offers a wider color gamut than Adobe RGB (right). The maximum illuminance is approximately 3000 lux.

Table 1. The CCT (K), illuminance (lux), *x*, *y*, delta *uv*, and color rendering index (CRI) of the lighting stimuli

Stimuli	CCT (K)	Illuminance (lux)	*x*	*y*	delta *uv*	CRI
1	3538	541	0.4043	0.3928	0.0010	83
2	5025	562	0.3446	0.3536	0.0012	89
3	6522	551	0.3132	0.3232	–0.0001	90

At the start of the experiment, four disposable electrodes were placed on the participants' wrists and ankles, as shown in Fig. 2. The participants were exposed to the three lighting

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stimuli in random order. For each stimulus, the participants were engaged in reading a novel on a screen so as to reduce stress due to boredom. To allow chromatic adaptation to take place [19], ECG recordings were done for two minutes after three minutes had elapsed. The signals were recorded using Laxtha Poly G-I equipment. There was a one-minute break between each lighting stimulus during which the participants were allowed to relax and move. The experiment lasted approximately twenty minutes.

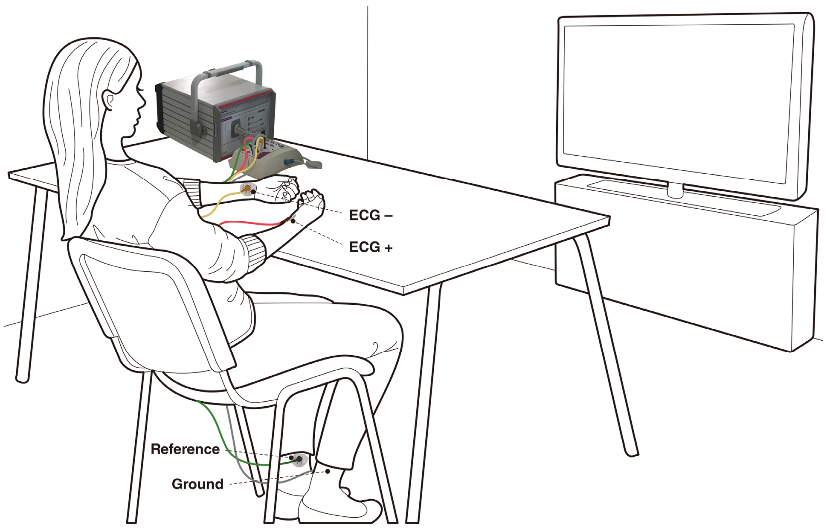

Fig. 2. Placement of the four electrodes (ECG + , ECG –, Reference, Ground) for electrocardiogram.

2.2 Results and discussion

For traditional ECG measurements, two main spectral components are distinguished: a low-frequency component (LF: 0.04-0.15 Hz) reflecting sympathetic arousal and a high-frequency component (HF: 0.15-0.4 Hz) reflecting vagal relaxation [20]. The ratio between the LF and HF component (LF/HF) is considered to be a measure of the sympatho-vagal arousal level [21]. The means (*M*), standard deviations (*SD*), *F* ratios (*F*), significances (*p*), and effect sizes (η_p^2) of the LF/HF ratio were reported, as shown in Table 2. A repeated measures ANOVA indicated that the LF/HF ratio differed statistically significantly between lightings ($F(2,32) = 4.61$, $p < 0.05$, $\eta_p^2 = 0.22$). The results of the study showed an increase in the LF/HF ratio during exposure to the 6500 K lighting ($M = 1.14$, $SD = 0.17$), indicating that the 6500 K lighting is arousing. In the 3500 K lighting, however, the LF/HF ratio was the lowest ($M = 1.07$, $SD = 0.15$), so this CCT can be considered the most relaxing. In psychology, the Yerkes-Dodson Law [22] posited that there is a curvilinear relationship between arousal and performance. The law dictates that up to a certain point, performance can increase with physiological arousal. Hence, the result of the preliminary study suggests that different lighting CCTs could evoke physiological arousal and relaxation, thereby facilitating different student activities. However, the effect of lighting CCTs on cognitive and behavioral aspects should be further investigated to provide consistent and unequivocal empirical evidence.

3. Study 1: laboratory experiment

3.1 Method

The laboratory experiment attempted to investigate the influence of different lighting CCTs on cognitive and behavioral responses. In total, 31 fourth-grade elementary school children were recruited with parental content. A total of twelve boys and nineteen girls with an average age of ten years participated in the study. Any children with learning disabilities were

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excluded from the sample. All participants were paid volunteers. They had normal or corrected-to-normal visual acuity with no significant color deficiencies. The specifics of the experimental setting, namely the furniture arrangement, lighting stimuli, and ambient conditions of the room, were consistent with those of the preliminary study.

A within-subjects design was adopted for the laboratory experiment. Children were grouped into six teams, and there were five to six children in each team, as shown in Fig. 3. They took part in a series of two representative class activities, namely academic and recess activities, during the lighting exposure. For an academic activity, students were asked to solve a set of arithmetic problems of medium-level difficulty, which included addition, subtraction, multiplication, and division. The problem sets were of comparable difficulty across the three lighting conditions. The mathematical tests were timed, and students were given 120 seconds to complete each set. The percentage of correct answers was assessed as the measurement of both accuracy and speed. The academic activity was followed by a recess activity, in which students were asked to communicate while facing their peers for 240 seconds. Previous researches suggest that the physical environment can significantly influence humans' affective states and, accordingly, individual time perception [23, 24]. The internal clock of time perception could be lengthened when a person is at the arousal end of the relaxation/arousal continuum. Hence, for each lighting exposure, the students were required to report in seconds how much time they believed had passed. One minute was given for chromatic adaptation prior to each activity [19]. Each activity was followed by the completion of cognitive measurements, in which students were asked to evaluate how appropriate each of the lightings were in terms of comprehension, concentration, visual comfort, and suitability based on a five-point Likert scale. The students were exposed to the three lighting stimuli in random order. The total time required was approximately thirty minutes.

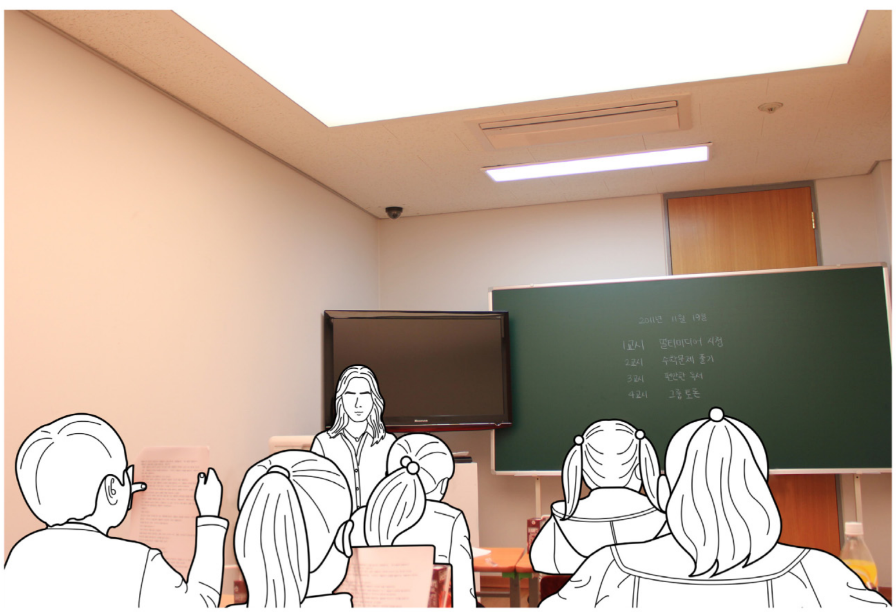

Fig. 3. Experimental setup for the laboratory experiment.

3.2 Results and discussion

A repeated measures ANOVA showed that there were no significant differences in cognitive measurements between the three lighting stimuli during the academic activity ($F(2,60) = 0.34$, $p = 0.70$, $\eta_p^2 = 0.01$) and the recess activity ($F(2,60) = 2.07$, $p = 0.14$, $\eta_p^2 = 0.06$), as shown in Table 2. On average, the preference for the three lighting conditions did not differ in both activities. Moreover, although the differences in the behavioral measurements were

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statistically significant in both the academic activity ($F(2,60) = 8.72$, $p < 0.05$, $\eta_p^2 = 0.23$) and the recess activity ($F(2,60) = 4.70$, $p < 0.05$, $\eta_p^2 = 0.14$), no meaningful interpretations were derived to relate the lighting CCTs and the human behaviors. The academic performance was the worst and the time seemed to pass most slowly under the intermediate 5000 K lighting. It can be suggested that this inconsistency in result arises due to the artificial test setting as well as the short lighting exposure period. Hence, a complementary study should be carried in a real-life setting with prolonged exposure.

Table 2. The results of the preliminary study (*N* = 17) and laboratory experiment (*N* = 31)[a]

Lighting Stimuli	Preliminary	Laboratory Experiment			
	LF/HF*	Academic Activities		Recess Activities	
		Survey	Answer* (%)	Survey	Time* (sec)
3500 K	1.07 (0.15)	4.15 (0.88)	82.65 (14.31)	3.92 (0.72)	235.84 (100.23)
5000 K	1.08 (0.15)	4.06 (0.91)	77.42 (13.82)	4.10 (0.74)	294.84 (141.85)
6500 K	1.14 (0.17)	4.06 (0.92)	86.05 (12.66)	3.85 (0.74)	247.55 (118.62)

[a]The mean and standard deviation of experimental results. An asterisk indicates significance at $p < 0.05$.

4. Study 2: field experiment

4.1 Method

The field experiment was designed as a pretest-posttest nonequivalent control group study to investigate the effect of different lighting CCTs when conventional fluorescent lighting was replaced with tunable solid-state lighting. Two fourth-grade classrooms within the same elementary school in the Republic of Korea were appointed as the control and experimental groups. All students received parental consent prior to the study. Any students with learning disabilities were excluded from the analysis. In all, a total of 54 responses were analyzed in the study: 27 students from the control group (fifteen boys and twelve girls) and 27 students from the experimental group (fifteen boys and twelve girls). The average age was ten years. All participants had normal or corrected-to-normal visual acuity with no significant color deficiencies.

The experiments were conducted every other day for a period of two weeks. During the pretest (first week), both groups were equipped with conventional fluorescent lighting. However, the lighting in the experimental group's classroom was replaced with tunable LEDs during the posttest (second week), as shown in Fig. 4. The classrooms were situated side by side on the second floor with the penetration of sunlight from one side. In order to minimize the fluctuation of natural daylight, the experiments were conducted early in the morning. The weather during the experiments was classified as cloudy by the Korea Metrological Administration. The lighting conditions produced in both classrooms were measured on a horizontal plane at the students' desk level, without natural daylight, using a chroma meter (Konica Minolta CL-200), as shown in Table 3. The average CCT of the original fluorescent lighting was around 5000 K with an illuminance of 500 lux for both classes. During the posttest, three lighting CCTs were controlled for the experimental room: 3500 K, 5000 K, and 6500 K. The illuminances were aimed to be adjusted to approximately 500 to 600 lux under ISO 8995 [17]. Although the maximum illuminance produced by 3500 K lighting did not reach 500 lux due to physical limitations, it was within the smallest significant difference in subjective effect of illuminance under ISO 8995.

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Table 3. The average CCT (K), illuminance (lux), and CRI of the pretest-posttest lighting conditions

Lighting Stimuli	CCT (K)	Illuminance (lux)	CRI
Fluorescent (Pretest)	4912	531	89
3500 K (Posttest)	3483	455	85
5000 K (Posttest)	4970	567	91
6500 K (Posttest)	6543	572	91

Fig. 4. The original fluorescent lighting (left) replaced with tunable LEDs (right).

During the two-week period, both groups were asked to solve a set of arithmetic problems during the lighting exposure. Similar to the laboratory experiment, the problem sets were of medium-level difficulty, and students were given 120 seconds to complete each set. During the posttest, the students in the experimental group were asked to complete surveys upon completing the mathematical tests. The students were asked to evaluate the appropriateness of each lighting stimulus for academic and recess activity in terms of comprehension, concentration, visual comfort, and suitability based on a five-point Likert scale. The lights of the experimental classroom were manipulated in random order during the posttest. The total time required to complete the experiment was approximately ten minutes.

4.2 Results and discussion

For cognitive measurements, a repeated measures ANOVA was conducted to observe the effects of lighting CCTs on the subjective appropriateness. The results indicated that there were statistically significant effects of lighting CCTs in both the academic ($F(2,52) = 3.32$, $p < 0.05$, $\eta_p^2 = 0.11$) and the recess activity ($F(2,52) = 3.25$, $p < 0.05$, $\eta_p^2 = 0.11$), as listed in Table 4. For academic activity, the 6500 K lighting was subjectively perceived as the most appropriate ($M = 4.27$, $SD = 0.65$), while 3500 K lighting received the highest average score for recess activity ($M = 3.72$, $SD = 0.74$).

Table 4. The mean and standard deviation of the appropriateness of the three lighting conditions ($N = 27$)[a]

Lighting Stimuli	Academic Activity*	Recess Activity*
3500 K	4.00 (0.96)	3.72 (0.74)
5000 K	4.20 (0.71)	3.39 (1.04)
6500 K	4.27 (0.65)	3.22 (0.98)

[a]An asterisk indicates significance at $p < 0.05$.

The means (M), standard deviations (SD), Student's t-values (t), significances (p), and effect sizes (Cohen's d) of the percentage of correct answers were reported, as shown in Table

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5. The results of paired samples t-test indicated that while there were no significant differences between the pretest and the posttest in the control group ($t(26) = 0.99$, $p = 0.33$, Cohen's $d = 0.15$, two-tailed), the percentage of correct answers increased during the posttest in the experimental group ($t(26) = 4.87$, $p < 0.05$, Cohen's $d = 0.83$, two-tailed). Moreover, although the students in the control group performed better on the mathematical test during the pretest ($t(52) = 3.60$, $p < 0.05$, Cohen's $d = 1.00$, two-tailed), no significant differences were observed between the two groups during the posttest ($t(52) = 0.47$, $p = 0.64$, Cohen's $d = 0.13$, two-tailed). However, it should be noted that the improvement in the experimental group was significantly larger than that of the control group. This suggests that the statistically significant differences found in the experimental group might have been caused by the change in the state of mind due to the lighting difference, and also by the fact that the experimental group had more room for improvement as their initial average score was lower than that of the control group. Hence, a repeated measures ANOVA was adopted to examine the differences within an experimental group. Among three lighting CCTs, the result indicated that the percentage of correct answers was the highest in the 6500 K lighting ($M = 65.00$, $SD = 18.73$), $F(2,52) = 9.99$, $p < 0.05$, $\eta_p^2 = 0.51$.

Table 5. The mean and standard deviation of the percentage of correct answers (%)

	Control Group (N = 27)		Experimental Group (N = 27)	
Pretest	Fluorescent	62.31 (13.55)	Fluorescent	49.35 (12.93)
Posttest	Fluorescent	64.91 (20.41)	3500 K	59.81 (19.77)
			5000 K	62.47 (16.71)
			6500 K	65.00 (18.73)

Although the laboratory experiments did not yield meaningful results, the results of the field experiment supported the effect of different lighting CCTs on both cognitive and behavioral performances, which concurs with the findings from the physiological responses. Although the exposure to natural daylight did not call into question the findings from the preliminary study, more systematic research is needed on the influence of the time of day in combination with artificial lighting conditions. Otherwise, a hybrid system of sunlight and LEDs [25] could be adopted in classrooms as an alternative solution for minimizing the fluctuation of natural daylight.

5. Dynamic lighting system for practical application

Three different lighting presets were suggested for a dynamic lighting system based on three complementary empirical studies and were given representative names that expressed the nature of the activities. The "easy" lighting preset provided a relaxing environment to support recess activities, such as communicating with peers. The average CCT was 3500 K with an illuminance level of 500 lux on a horizontal plane at the students' desk level. The "standard" lighting preset could be applied for regular activities such as reading, with a CCT of 5000 K and an illuminance of 500 lux. The "intensive" setting supported students' performance during intensive academic activities, such as problem solving. The average CCT was 6500 K with an illuminance level of 500 lux.

Using the three lighting presets derived from the empirical study, a dynamic lighting system was designed as a mobile application to generate highly optimized lighting according to students' activities. The application allowed teachers to select the most appropriate lighting via three lighting presets: "easy," "standard," and "intensive" modes, as shown in Fig. 5. In addition, the teachers were able to adjust the illuminance level by pinching in and out the intensity icon, according to the fluctuation of natural daylight. Figure 6 illustrates the operational flow of the dynamic lighting system implemented in the practical application. An intuitive dynamic lighting system is expected to help teachers to support students' performance according to the rhythm of activities in the classroom.

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Fig. 5. Dynamic lighting system implemented as a mobile application with three lighting presets.

Fig. 6. Operational flow of the dynamic lighting system: 1) students are focusing on solving mathematical problems; 2) select the "intensive" lighting preset to support students' academic performance; and 3) lower the illuminance level by pinching in the intensity icon for high intensity of daylight.

6. General discussion

With a comprehensive analysis of three different empirical studies, a total of three lighting presets were suggested for a dynamic lighting system. However, there are prevalent limitations to this study. First, although the results from the preliminary study and the field experiment supported that lighting CCTs influence the physiological, cognitive, and behavioral response, the results from the laboratory experiments failed to produce a consistent result. A plausible explanation for the lack of meaningful in-lab results is that the test subjects were placed in an artificial setting and exposed to the lightings for only a short time. Additionally, due to physical limitations, the illuminance level was set to 455 to 572 lux in the field experiment. Although the difference between the two illuminance levels fall within the range of detectable difference, the effect of illuminance level in combination with different CCTs should be verified before applying the lighting presets. Moreover, the exposure time for each lighting condition was two to three minutes, which was much shorter than the normal class period. According to the Yerkes-Dodson Law [22], performance decreases when the level of arousal becomes too high. Thus, it should be verified whether the

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results change when subjects are exposed to the lightings for longer period, and future work could be done to investigate the ideal exposure time for each lighting condition.

The influence of different lighting CCTs on students' performance was also supported by two recent studies conducted in Germany and the Netherlands [15, 16]. In particular, the positive effect of high CCT on human arousal was also observed in working environments [10, 11]. However, that does not necessarily mean that the higher the CCT, the better the performance is. There might be a point of diminishing returns at which higher CCT no longer improves human performance. As such, future work is necessary to examine the diverse range of lighting CCTs in learning environments. Moreover, unlike lighting colors, the effect of wall colors on students' performance has long been investigated in the field of interior design and has already been applied for school interiors [7, 26]. By simply changing the lighting conditions, the properties of visual appearance in the interiors could be also affected, and hence, total visual appearance [27] should be investigated for practical application. Moreover, supplementary studies with different age groups are necessary for the proposed dynamic lighting system to be applicable for general learning environments. Although further research is necessary, the present study builds on and extends earlier studies with increased insights that could act as a good stepping stone for implementing dynamic lighting systems in learning environments.

7. Conclusion

The purpose of this study was to identify the effects of different lighting CCTs on elementary students' performance, which can be applied as the basis for developing a dynamic lighting system in learning environments. Although the results from the laboratory experiment were not meaningful enough, the preliminary study and the field experiment fully supported a positive effect of 6500 K lighting on academic performance, and 3500 K lighting on encouraging recess activities. Accordingly, a total of three lighting presets were suggested: "easy," "standard," and "intensive" modes with a CCT of 3500 K, 5000 K, and 6500 K, respectively. Although further research is necessary, the dynamic lighting system proposed in this study is expected to be applied as the basis for designing a user-centered lighting control system and thereby facilitate students' performance according to the rhythm of activities.

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