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Melatonin Suppression under LED Lighting Focused on Spectral Power Distribution Differences

Seong-Kwan Hong* · Kyoung-Sil Kim · In-Tae Kim · An-Seop Choi**

Abstract

Changes in melatonin concentration levels by differences in CCT of white LED light focused on Spectral Power Distribution (SPD) differences compared to the same CCT of conventional fluorescent light were analyzed. For this, melatonin concentration levels in saliva samples were taken over four different experiments at seven-day intervals. In 71.4% of participants, it was confirmed that melatonin concentration is suppressed by exposure to light, and a slight difference was observed by different CCTs. In addition, Experiment II with a high CCT was relatively high in terms of the melatonin suppression rate compared to Experiment III. A key finding was the possibility that different SPDs under a particular CCT of white LED light compared to the same CCT of conventional fluorescent light could have the same effect on the melatonin suppression.

Key Words : Circadian Rhythm; Correlated Color Temperature (CCT); Melatonin Suppression; Spectral Power Distribution (SPD); White LED Luminaire

1. Introduction

Light increases human perception and has an effect on circadian rhythm, which is the biological process that occurs over the course of 24 hours. It is driven by a circadian clock and has been widely observed in plants, animals, and humans[1]. An imbalance of one's circadian rhythm can cause disorders such as seasonal affective disorder and jet lag syndrome[2-3]. People currently tend to experience fatigue because of the collision between lifestyle and circadian rhythm[4], of which one typical issue is shift work disorder.

Melatonin, one of the hormones associated with circadian rhythm, is a neuro-hormone released from the pineal gland at night. It plays a critical role in changing physiological functions, and the circadian pattern of melatonin is the highest in those in their early teens and the lowest in those in their 60s or older. Effects on melatonin concentration vary depending on light characteristics (intensity and wavelength) and time (exposure time and exposure period)[5-9]. Therefore, a study on melatonin suppression by

* Main author : Ph.D Candidate, Department of Architectural Engineering, Sejong University
** Corresponding author : Professor, Department of Architectural Enginnering, Sejong University
Tel : 02-3408-3761, Fax : 02-3408-4331
E-mail : aschoi@sejong.ac.kr
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artificial lighting is needed for individuals who are exposed to artificial lighting for extended periods indoors. In studies on light characteristics, the effect of light intensity on melatonin was examined[10].

There have been many studies on how to apply lighting to an indoor space based on the results of the previous studies mentioned above. Studies on human reaction according to illuminance level and color temperature have been conducted. In order to assess the effects of prolonged exposure to low intensity light (E< 500lx), from a light source with a high CCT (17,000K vs. 2,700K) behavior and circadian rhythm of institutionalized older adults with dementia[11] were examined. In the bluish light scenario, a significant improvement in restless behavior was observed in the intervention group, as well as a significant increase in the range of tympanic temperature. These effects were not found in the yellowish light scenario. Further evidence is found that high-intensity bluish light may play a role in managing restless behavior and improving circadian rhythm in institutionalized older adults with dementia[12]. To estimate dim light melatonin onset and to analyze the phase angle relationship between dim light melatonin onset and the sleep period, IW Saxvig et al. revealed that sleep and dim light melatonin onset were delayed in participants with delayed sleep phase disorder[13]. The results of Y Zhu et al.'s study indicate that most circadian genes showed significant advances in circadian phase between 1 ~2 weeks for participants in both the blue-light and dim-light groups[14].

Studies on the evaluation and measurement of the circadian effects of light were also carried out. To investigate such effects, P. B. Boyce reviewed advanced research projects related to light as radiation, light operating through the visual system, and light operating through the circadian system[15]. L. Bellia et al. also proposed an easy way to evaluate the potential circadian effects of light sources[16]. In addition, M. G. Figueiro et al.'s study was conducted with eighth-grade students to determine the impact of morning light on circadian timing, sleep duration, and performance using the Daysimeter, which can measured light/dark exposures[17].

These circadian rhythm-related studies mostly use special LED lights (Red, Green, and Blue LEDs), but such lights cannot be used in a normal life pattern. In addition, fluorescent lamps, for which luminous environment conditions are difficult to control, were used. Therefore, this study aimed to determine changes in melatonin concentration levels caused by differences of CCT within a range applicable to an actual living space using LED lights that can be substituted for a conventional light source. They can be easily controlled with diverse illuminance and CCT levels through the dimming technology and combination of LED devices. Because other conventional light sources such as fluorescent lamps differ from SPD even under the same CCT condition, a further analysis of different SPD effects on melatonin suppression is necessary to apply dimmable LED luminaire considering circadian rhythm. SPDs of light sources affect not only CCT of light sources, but also chromaticity XY-coordinates, which eventually can affect color appearance and its impacts on human biological rhythms. In this study, therefore, changes in melatonin concentration levels by different CCTs were compared and analyzed in a space in which dimmable LED luminaires were installed. A healthy visual environment can be created by applying preliminary findings from this study.

2. Experiment

2.1 Experimental Method

This study analyzed melatonin concentration levels in order to determine the effect of LED lights on circadian rhythm. For this, such levels were measured through saliva, and participants were required to fast for at least 1 hour before saliva sampling. The samples were immediately stored in a freezer (-40℃) as per a recommendation by a laboratory (N lab). N lab used VERSA Max for analysis of melatonin concentration levels and chose Enzyme-Linked Immunosorbent Assa (ELISA) as the test method. All data measurements were sorted and analyzed by melatonin suppression through the relative melatonin graph.

Tests were performed from 21:00 to 02:30 with 10 graduate students (5 men and 5 women). Participants were asked to fill out questionnaires of their life patterns during the experiment period including coffee and alcohol intake, and any abnormal activities. The outline of experiment subjects is shown in Table 1.

Table 1. The outline of experiment subjects

Subject	Age	Subject	Age
M1	31 years	W1	24 years
M2	28 years	W2	22 years
M3	27 years	W3	22 years
M4	26 years	W4	22 years
M5	25 years	W5	21 years

This test was carried out in a lecture room in which dimmable LED luminaires were installed. All experiments were conducted with a constant temperature and humidity.

The dimmable flat LED luminaire installed in the test space consisted of four LED devices: 2,650K, 3,650K, 5,200K, and 6,600K. The test space was designed to implement various illuminance and CCT levels (Fig. 1). The illuminance value of 400lx was implemented to satisfy the general target illuminance level at the workplane. In addition, the CCT values of 3000K and 6000K were chosen to represent maximum and minimum values for the typical range of indoor luminous environment, respectively. A dimmable LED luminaire could be controlled over diverse illuminance and CCT levels

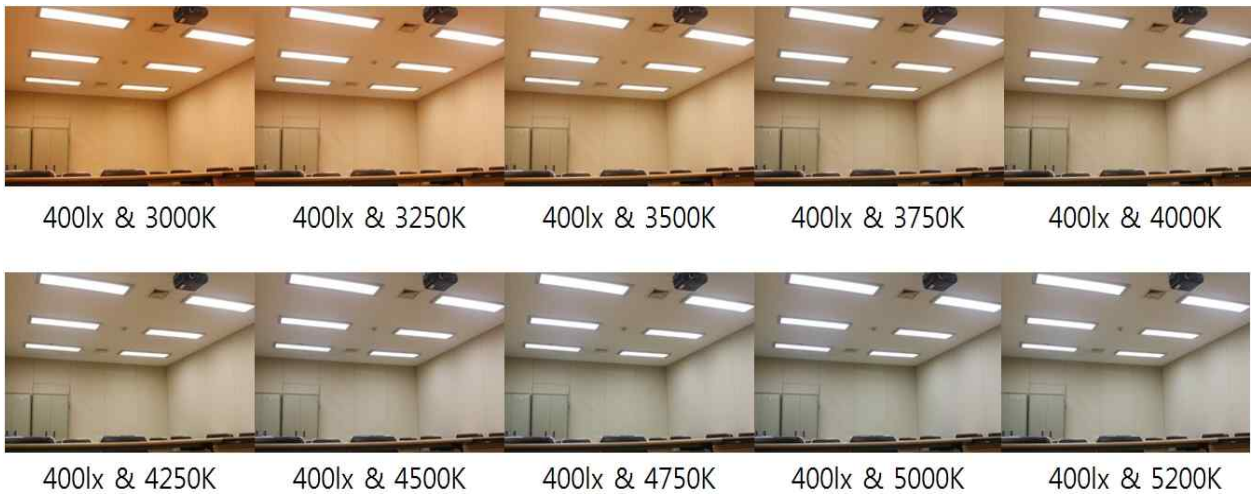

Fig. 1. The various CCT levels in the test space

through dimming software. Through a combination of four LED devices, the target lighting conditions of 3,000K/400lx and 6,000K/400lx were utilized by controlling the steps of each LED device in dimming software carefully. Fig. 2 shows the structure of installed luminaires, two different SPDs of installed LED luminaires, and the SPDs of fluorescent lamps as a reference. As stated in previous section, the SPDs of LED light is quite different from those of fluorescent lamps.

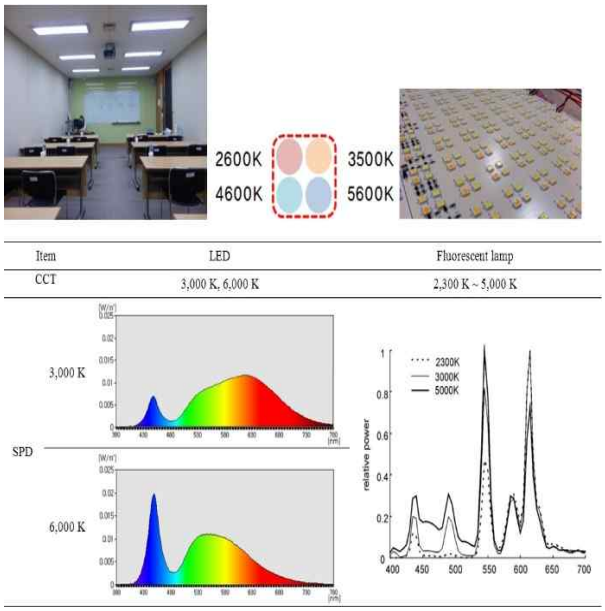

Fig. 2. The view of the installed luminaire, SPDs

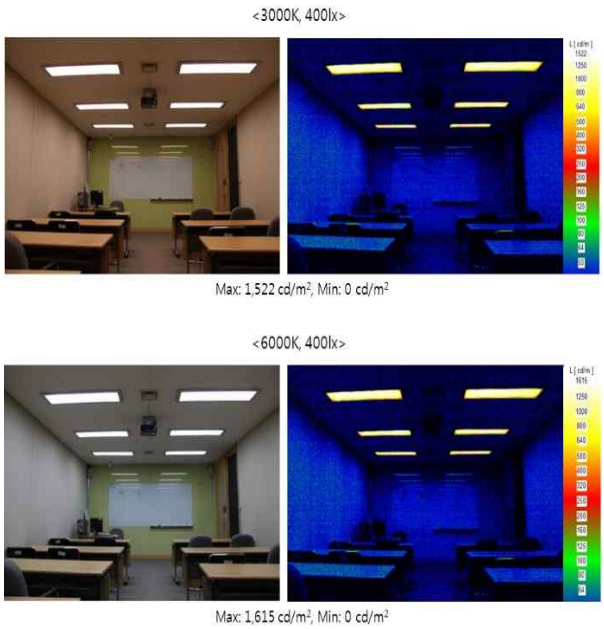

Fig. 3. The luminance distribution within the whole field of view

Fig. 3 illustrates the luminance values at the subject's eye level under the target luminous conditions by a luminance imaging measurement, which shows the luminance distribution within the whole field of view.

2.2 Design of Experiment

This study consisted of four different experiments. Each experiment was performed once a day for four different days, and saliva was collected four times per experiment. In consideration of participant circadian rhythm, the test continued at one week intervals. Fig. 4 shows the design of the experiment. Participants stayed awake during Experiments I, II and III, whereas they went to sleep after staying awake for three hours in Experiment IV.

Experiment I aimed to determine participant melatonin concentration and secretion pattern. For this, saliva was collected under dim light (4,500K/ 10lx). Fig. 5 shows the picture of saliva sampling from participants under the luminous environment of Experiment I. Testing was performed from 24:00 to 02:30.

Experiments II and III targeted the determination of changes in melatonin concentration by two different CCTs of dimmable LED luminaire. These tests were performed from 23:00 to 02:30. Experiments II and III were carried out under the target lighting conditions of 3,000K/400lx and 6,000K/400lx, respectively. In terms of experiment

		21:00		22:00		23:00		24:00	01:00		02:00		02:30
Experiment I		Test is not conducted						Take saliva	4,500 K, 10 lx	Take saliva	4,500 K, 10 lx	Take saliva	4,500 K, 10 lx	Take saliva
Experiment II		Test is not conducted				Take saliva	4,500 K, 10 lx	Take saliva	6,000 K, 400 lx		Take saliva	6,000 K, 400 lx		Take saliva
Experiment III		Test is not conducted				Take saliva	4,500 K, 10 lx	Take saliva	3,000 K, 400 lx		Take saliva	3,000 K, 400 lx		Take saliva
Experiment IV	**Group1**	Take saliva	3,000 K, 400 lx	Take saliva	3,000 K, 400 lx			Take saliva	Sleep					Take saliva
	Group2	Take saliva	6,000 K, 400 lx	Take saliva	6,000 K, 400 lx			Take saliva	Sleep					Take saliva

Fig. 4. The design of experiment

design, dim light (4,500K/10lx) lasted for one hour (23:00-24:00). Beginning at midnight, the test was performed under the target lighting conditions as shown in Fig. 4. Experiments II and III therefore attempted to compare changes in melatonin concentration levels when participants were exposed to LED light with different CCTs under the same time zone and same illuminance.

Fig. 5. The picture of experiment (Experiment I)

Experiment IV was designed to consider the LED light conditions implemented in Experiments II and III as applied to an actual living pattern. This experiment aimed to determine changes in melatonin concentration levels under different luminous environment conditions after dividing participants into two groups (five persons each) on the same day. Experiment II and III were designed to compare the melatonin suppression level of each participant with different CCT conditions at two different days while Experiment IV targeted comparing the melatonin suppression levels of all participants with different CCT conditions on the same day. In addition, Experiment IV was designed to consider the actual living pattern. The space was divided with a blackout cloth to provide different luminous environment conditions (Fig. 6). In Group 1, participants were exposed to 3,000K/400lx (as in Experiment III) for three hours (21:00 - 24:00). Meanwhile, participants of Group 2 were exposed to 6,000K/400lx (as in Experiment II) for the same hours. They then resumed sleeping for two and half hours beginning at midnight. Therefore, Experiment IV attempted to determine the effect of the application of the results of Experiments II and III to the actual living pattern of the participants.

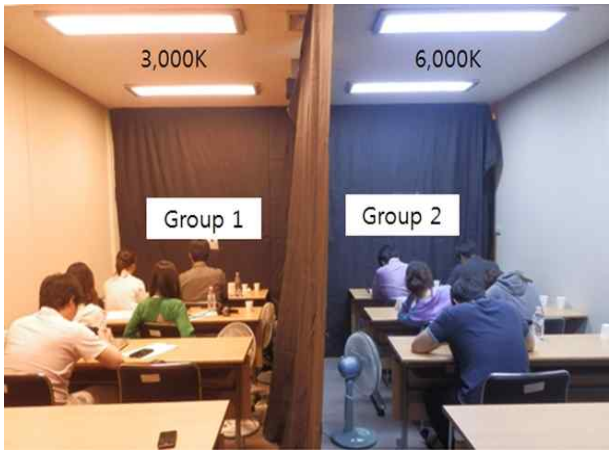

Fig. 6. The view of experiment (Experiment IV)

3. Results

3.1 Experiment I : Melatonin Concentration and Pattern

Experiment I aimed to determine general melatonin concentration under dim light. Because dim light (<10lx) does not affect circadian rhythm[14], the secretion of melatonin was confirmed through Experiment I. According to the analysis, melatonin was found in all participants. Among the ten participants, however, it was detected only once in four attempts in two participants (M3 and W3). The reason why nothing was detected in three attempts is due to the limitations of the Micro plate reader (VERSA Max) as the equipment could not measure 858.5pg/ml or higher values. Among the other eight participants, no value was detected once in four attempts in two participants (M2 and M5). Such results were taken into consideration for further detailed analysis.

According to an analysis of participant melatonin concentrations in Experiment I, concentration levels varied greatly by participant. A 10pg/ml or less value was detected once in four attempts. A 70pg/ml or more value was observed as well. Absolute melatonin concentrations can be compared to a participant individually but comparison with other participants is not a purpose of this study. Therefore, a relative scale graph that takes an individual's maximum melatonin concentration as "1" is shown in Fig. 7. The results of two participants (M3 and W3) were excluded from the analysis, and the results of two other participants (M2 and M4) were interpolated and shown on a dotted line.

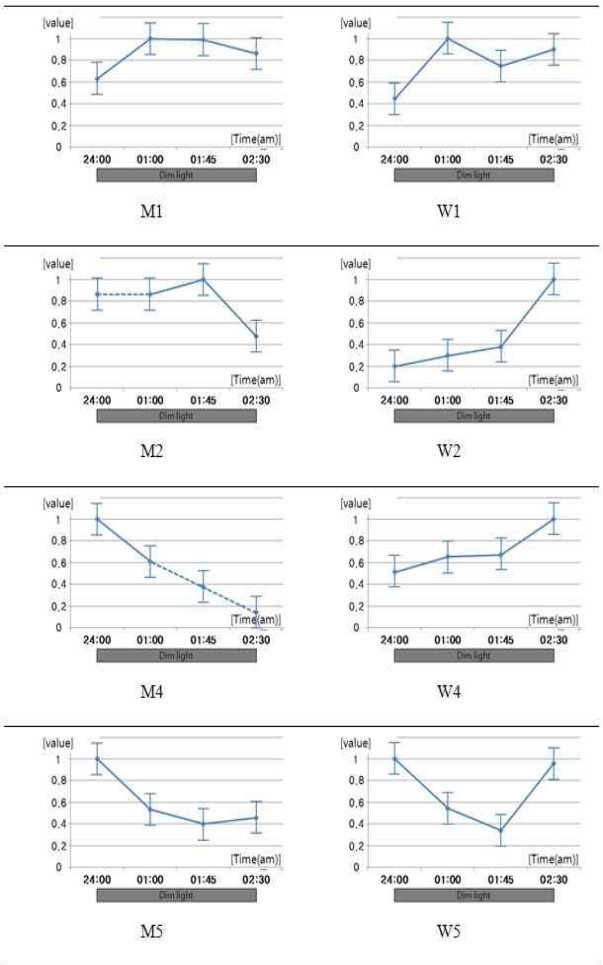

Fig. 7. Relative melatonin concentration from Experiment I (value ± error range)

According to an analysis of participant secretion pattern based on the result of Experiment I, the

patterns varied by participant as well. Although it was anticipated that melatonin levels would increase after midnight, it partially declined in most male participants. This occurred because participant melatonin level declined instantly after being exposed to light and remaining awake. Melatonin levels for the most part increased in female participants except for W5. In fact, they were on the rise in all participants following the 3rd measurement (01:45). A one-way analysis of variance (ANOVA) was carried out for melatonin relative melatonin concentration and absolute melatonin concentration. A one-way ANOVA (relative) showed no significant differences of melatonin concentration ($P \geq 0.05$) among all subjects [$F(7,24)=0.99$, $P=0.4632$]. A one-way ANOVA (absolute) also showed no significant differences of melatonin concentration ($P \geq 0.05$) among all subjects [$F(7,24)=1.64$, $P=0.1724$].

3.2 Experiments II and III : Comparison of Suppression Effect by Difference in CCT

The absolute melatonin concentrations were compared between Experiment I, and Experiments II and III. The result of Experiment I was regarded as the control group. The luminous environment conditions of each experiment are shown in Fig. 4. Since the illuminance levels were different in Experiments II and III compared to that of Experiment I, the effect of light on melatonin can be determined by comparing absolute concentrations. Except for two participants (M3 and W3) who had no result in Experiment I and one participant (W5) who could not be compared because of an absence in Experiment III, the absolute melatonin concentrations were compared among the remaining seven participants (at 02:30). As shown in Table 2, the melatonin concentrations were greater in Experiment I than in Experiments II and III in five out of seven participants. In the remaining two participants, the median between Experiments II and III was stated. This shows that melatonin was suppressed by being exposed to light in five (71.4%) out of seven participants.

Table 2. The comparison of absolute melatonin concentration values (Experiment I vs. Experiments II and III)

Level relation	Participants
Experiment I > Experiment II& III	M1, M2, M4, M5, W2 (5 people)
Experiment III > Experiment I > Experiment II	W1, W4 (2 people)

Fig. 8 shows the graph of relative melatonin concentration from Experiments II and III. As in Fig. 5, there are interpolations shown on a dotted line. In the case of W5, the result of Experiment II (6,000K) was added only because the subject was unable to participate in Experiment III.

Because the goal of Experiments II and III was to compare changes in melatonin concentration by different CCTs, the slope was analyzed after dividing luminous environment conditions into two sections: 24:00-01:15 and 01:15-02:30. This slope enables the determination of changes in melatonin concentration over time where slope means divide the increment of the y axis by the increment of the x axis. Except for W5, who was incomparable because of absence from Experiment II, and W2, who showed the opposite results compared to other participants' tendencies, the remaining eight participants were compared.

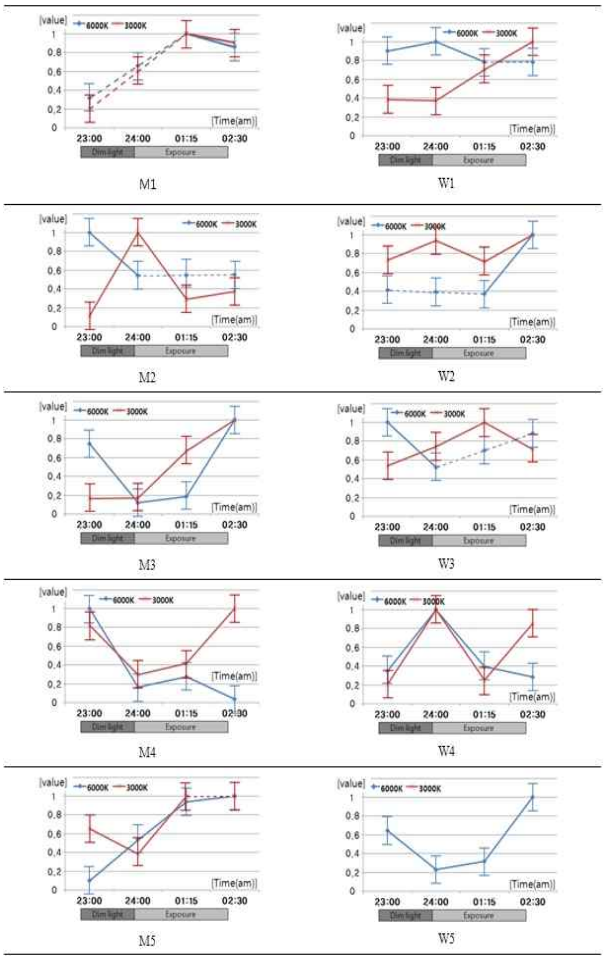

Fig. 8. Comparison of relative melatonin concentration from Experiment II and III (value ± error range)

Based on the results of the previous studies in section 1, which found that melatonin concentration was further suppressed as CCT increases, it was forecasted that the slope would be gentler at high CCT (6,000K) than in low CCT (3,000K). The slope was gentler in 6,000K than in 3,000K in 75% of participants in the 24:00–01:15 zone and 50% of participants in the 01:15–02:30 zone. Therefore, it could be concluded that melatonin suppression was greater in 6,000K than in 3,000K in more than half of the participants. A one-way ANOVA (relative, 6,000K) showed no significant differences of melatonin concentration ($P \geq 0.05$) among all subjects [$F(9,30)=0.81$, $P=0.6126$]. On the contrary, a one-way ANOVA (absolute, 6,000K) showed some differences of melatonin concentration ($P<0.05$) among all subjects [$F(9,30)=3.41$, $P=0.0054$]. A one-way ANOVA (relative, 3,000K) showed no significant differences of melatonin concentration ($P \geq 0.05$) among all subjects [$F(8,27)=0.62$, $P=0.7544$]. A one-way ANOVA (absolute, 3,000K) showed some differences of melatonin concentration ($P<0.05$) among all subjects [$F(8,27)=3.91$, $P=0.0035$] as in the case of 6,000K.

3.3 Experiment IV: Analysis of Changes in Melatonin Concentration during Sleep

Experiment IV attempted to compare changes in melatonin levels while participants were asleep (24:00–02:30, two and half hours) after exposing them (Group 1 and Group 2) to different luminous environment conditions from 21:00 to 24:00 (See Fig. 2). In Table 3, the percentage of increase in melatonin concentration levels from 24:00 to 02:30 was calculated after dividing the melatonin results from Experiment IV into two groups: Group 1 and Group 2. An increase in melatonin levels during sleep was analyzed except for two participants (M3 and W4) who were off from the average range. The result at 02:30 increased by about 46% on average compared to the result at midnight in Group 1. In Group 2, the result increased by about 36% on average. Because participants slept in a dark space, increased melatonin levels were observed in both groups. In terms of melatonin concentration growth, Group 1 was greater than Group 2 by about 10%. Therefore, it could be concluded that when participants are exposed to light while they are

awake (21:00-24:00), the suppression effect is greater with a high CCT.

Table 3. Results of melatonin concentration (Experiment IV). Two participants (W4 and M3) who were off from the average range are ruled out

Group	Participant	Melatonin concentration (pg/ml)		Increase rate
		24:00	02:30	02:30/24:00
G 1 3,000K	M1	51.6	74.2	1.44
	M4	15.7	24.8	1.58
	W1	65.5	65.5	1
	W2	41.4	75.9	1.83
	W4	56.2	46.5	0.82
	Average	-	-	1.46
G 2 6,000K	M2	46.6	46.4	1
	M3	1.8	30.5	16.94
	M5	32.2	45.2	1.40
	W3	75.5	100.1	1.33
	W5	20.2	34.8	1.72
	Average	-	-	1.36

Experiment IV, and Experiments II and III were conducted under different time zones, but the same luminous environment conditions were provided. The results (Table 4) were analyzed except for three participants (M2, W1, and W5), who could not be compared as there were no result values for them. As shown in Table 2, the result from Experiment II was greater than that from Experiment IV in terms of melatonin concentration levels at 02:30 in Group 2. In the case of Group 1, on the contrary, the result from Experiment IV was greater than that from Experiment III in 75% of participants. According to previous studies, the exposure to light at night could suppress melatonin concentration. In this experiment, exposure to light in the evening (21:00-24:00) instead of at night (24:00-02:30) at 6,000K has a larger effect on melatonin suppression. At 3,000K, on the other hand, it has a lower effect on melatonin suppression. A one-way ANOVA (relative, G1) showed no significant differences of melatonin concentration ($P \geq 0.05$) among subjects in the Group 1 [$F(4,15)=0.35$, $P=0.8404$]. A one-way ANOVA (absolute, G1) also showed no significant differences of melatonin concentration ($P \geq 0.05$) among subjects in the Group 1 [$F(4,15)=2.00$, $P=0.1463$]. Next, a one-way ANOVA (relative, G2) showed no significant differences of melatonin concentration ($P \geq 0.05$) among subjects in the Group 2 [$F(4,15)=0.27$, $P=0.8903$]. A one-way ANOVA (absolute, G2) also showed no significant differences of melatonin concentration ($P \geq 0.05$) among subjects in Group 2 [$F(4,15)=1.30$, $P=0.3161$].

Table 4. The comparison of absolute melatonin concentration values

Level relation	Number of participants
Experiments II > Experiments IV (Group 2)	3 people (Among 3 people)
Experiments IV (Group 1) > Experiments III	3 people (Among 4 people)

4. Conclusions

This research was conducted to help maintain circadian rhythm by controlling the luminous environment condition especially for changing CCTs. A key finding was the possibility that different SPDs under the same CCT (LED light vs. Fluorescent lamp) could have the same effect on melatonin suppression.

According to Experiment I, it was confirmed that melatonin is secreted in all participants, and the absolute melatonin concentrations and secretion

patterns vary greatly by participants. This kind of result is natural as absolute concentrations and life patterns vary among all individuals.

In Experiments II and III, which were performed in other luminous environment conditions, the difference in melatonin concentration growth over time was not significant. In most participants, however, melatonin suppression was relatively greater at 6,000K than 3,000K. In previous studies, the effect of CCT on melatonin concentration was analyzed for fluorescent lamps,[18] which showed that melatonin suppression was greater in 5,000K than in 2,300K by about 47%. Comparing the results of this study to those of previous studies, the effect on melatonin concentration could differ due to the different SPDs even under the same CCT in LED lights. However, the fact that melatonin suppression was greater at a high CCT than at a low CCT was the same.

According to Experiment IV, it was found that the effect on melatonin suppression with exposure to LED light at 6,000K in the evening is greater than that with exposure to LED light at 3,000K. After comparing the results of Experiments II, III and IV, different melatonin suppression effects were observed when participants were exposed to light at different times even under the same luminous environment condition. Therefore, light exposure is critical in implementing a lighting system considering circadian rhythm.

The result of this study implies that melatonin suppression by LED lights was relatively greater at 6,000K than 3,000K. This study confirms that effects of LED light and fluorescent light exposures on melatonin suppression were fairly similar even under different SPDs at the same CCT.

Recently, there has been a great amount of research and development regarding circadian lighting systems or automatic lighting control systems in architectural spaces. Such systems can control the illuminance and CCT levels of lighting systems, which can improve the luminous environment in architectural spaces and ultimately support occupants' well-being in the psychological and physiological aspects. The LED lighting system can easily control the illuminance levels and change the CCT levels compared to the conventional lighting system using fluorescent lamps. Based on occupants' schedule and their circadian rhythm, illuminance levels and CCT level can be lowered automatically at night.

This study has a limitation that the experiments were conducted with a relatively small test sample, and further studies need to be conducted to analyze melatonin suppression in more varied conditions to propose a more specific lighting system that could be applied to an actual architectural space.

Acknowledgement

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Biography

Seong-Kwan Hong

He received an M.S. degree from the Dept. of Architectural Engineering, Sejong University, Korea, in 2010. He is now a Ph.D. candidate at Sejong University, Korea.

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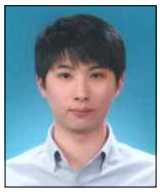

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He received an M.S. degree from the Dept. of Architectural Engineering, Sejong University, Korea, in 2012. He is now a Ph.D. candidate from Sejong University, Korea.

An-Seop Choi

He received an M.S. degree in the Dept. of Architectural Engineering from The Pennsylvania State University, USA, in 1993 and a Ph.D. in the Dept. of architectural engineering from The Pennsylvania State University, USA, in 1997. He is now a professor at Sejong University, Korea and a director of the Korea Committee of KIIEE.