The Control Method for Wavelength-Based CCT of Natural Light Using Warm/Cool White LED

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Abstract

Reproducing circadian patterns of natural light through lighting requires technology that can control correlated color temperature (CCT) and short wavelength ratio (SWR) simultaneously. This study proposes a method for controlling wavelength-based CCT of natural light using LED light sources. First, the spectral power distribution (SPD) of each channel of the test lighting (two-channel LED lighting with warm white and cool white) is identified through actual measurement. Next, CCT and SWR are calculated based on the additive mixing of SPD using the mixing ratio from the measured SPD. Finally, the regression equations for mixing ratio-CCT and mixing ratio-SWR are derived through regression analysis. These equations are then utilized to implement a wavelength-based CCT control algorithm. For performance and evaluation purposes, natural light reproduction experiments were conducted, achieving a mean error of 94.5K for CCT and 1.5% for SWR.

Keywords: natural light, spectral power distribution, CCT, short wavelength ratio

1. Introduction

The development of artificial light has made it possible for humans to engage in activities without the constraints of time and space, but it has also caused an imbalance in circadian rhythms [1-3]. To solve this problem, various studies have been conducted to provide the characteristics of natural light by utilizing LED light sources. In related studies, a lighting system that reproduces the circadian correlated color temperature (CCT) of natural light has been investigated using lights with CCT control in the range of about 2,700-6,800 K [4-5]. However, this study only aimed to reproduce the CCT of natural light, thus considering only visual reproduction and not circadian rhythms [6].

In another related study, to consider human circadian rhythms, the circadian CCT of natural light was reproduced while controlling the short wavelength ratio (SWR) according to the human wake-sleep cycle [7]. SWR is the percentage of short wavelengths (380 to 480 nm) in the visible light spectrum (380 to 780 nm), a factor proven effective in animal experiments [8]. However, this study did not reproduce the circadian SWR of natural light; instead, it simply controlled it to the highest or lowest SWR. As a result, the criteria for circadian lighting were ambiguous. In addition, although many studies have emphasized the connection between human circadian rhythms and the spectral power distribution (SPD) of natural light, there are technical limitations to reproducing the SPD of natural light through artificial light [9-10].

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The SPD of light can be measured with a spectrometer. SPDs serve as raw data that can represent light and contain information on illuminance, CCT, color rendering index (CRI), and SWR. These are commonly used units to measure light [11-12]. These SPDs have the advantage of allowing additive mixing of SPDs according to Grassmann's color mixing law, which means that SPDs for mixed light can be simulated without the need for actual measurements [13-15]. The SPDs of natural light and LEDs have different shapes because they generate light energy in different ways [16-17]. Therefore, it is technically difficult to reproduce the SPD of natural light using LEDs [18]. Therefore, it is necessary to analyze natural light and apply it to lighting using factors such as SWR and melanopic to photopic ratio, which are known to be related to human circadian rhythms, rather than reproducing the same SPD of natural light [19-22]. However, there is a lack of research in this field.

This study proposes a method to control the wavelength-based CCT of natural light using LED light sources. The proposed method aims to reproduce the natural light circadian pattern based on CCT and SWR, which are factors responsible for visual and non-visual effects (circadian rhythm), respectively. However, since natural light and LEDs have different light emission principles, it is difficult to reproduce natural light that satisfies CCT and SWR simultaneously. To improve the reproduction performance of SWR, a visually indistinguishable level of CCT tolerance is required. For this purpose, the CCT range (about ±100K) of the 4-step MacAdam ellipse is set as the CCT tolerance [23-24].

Therefore, for an improved SWR reproduction performance using CCT tolerance, a wavelength-based CCT control algorithm is developed and applied to lighting control. This algorithm facilitates LED lighting that contributes positively to the maintenance of circadian rhythm. To evaluate the performance, the proposed algorithm and a simple CCT control method were compared in a natural light reproduction experiment, and the proposed algorithm had a higher SWR reproduction performance. This study presents a generalized lighting control method for reproducing wavelength-based CCT of natural light for maintaining circadian rhythm only for lighting consisting of two LED light sources, warm white, and cool white, which are relatively easy to fabricate.

2. Wavelength-Based CCT Control Algorithm

The purpose of this study is to reproduce the circadian pattern of CCT and SWR in natural light. For this purpose, an algorithm was implemented to control the target CCT and SWR within the CCT tolerance of a 4-step MacAdam ellipse. Fig. 1 shows the derivation procedure of the wavelength-based CCT control algorithm, which consists of three steps.

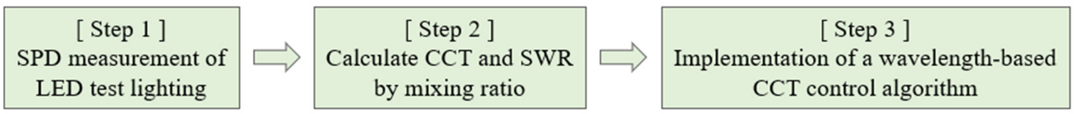

Fig. 1 Derivation procedure for wavelength-based CCT control algorithms

In step 1, the SPD of each channel of the two-channel LED test lighting was identified through measurement experiments. In step 2, CCT and SWR by mixing ratio were calculated through additive mixing of the measured SPDs based on Grassmann's color mixing law. In step 3, regression analysis was used to derive the regression equations of mixing ratio-CCT and mixing ratio-SWR, respectively, and then the wavelength-based CCT control algorithm was implemented using the derived regression equations.

2.1. SPD measurement of LED test lighting

In this study, a two-channel LED test lighting (Channel 1: 2,700K, Channel 2: 6,800K) was used. Each channel uses a current-controlled dimming method to control brightness, and the control level is configured for 256 (0-255, 0: off, 255: max) steps, and the control level and the brightness of the light source are proportional to each other. To accurately measure the SPD of the test lighting, a high-performance spectrometer (CAS-140CT, instrument systems) with a spectral resolution of 2.7

nm and a spectral range of 200 to 800 nm was used in a dark room with limited external light entry. The distance between the test lighting and the spectrometer receiver was set to 1,500 mm (domestic standard measurement distance for general lighting), and the control level of each channel was controlled to the maximum value of 255, followed by a stabilization time of about 10 seconds. Fig. 2 shows the measured SPD of each channel.

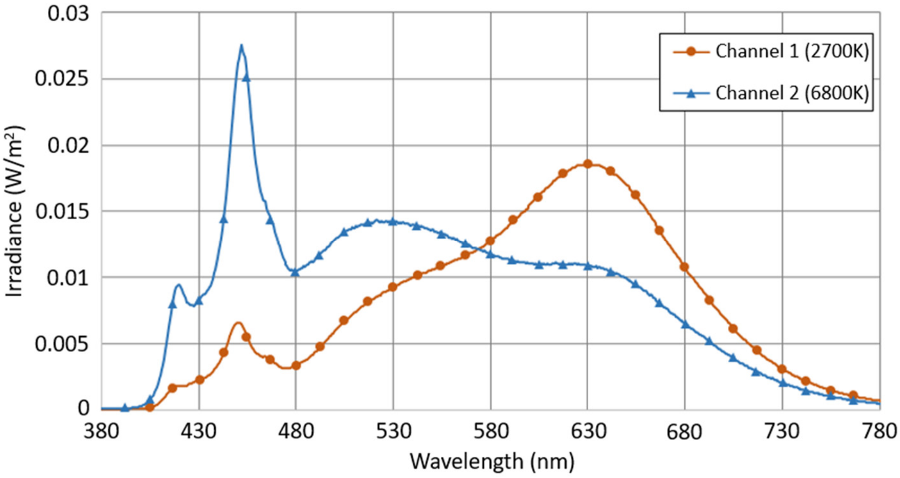

Fig. 2 SPD for each channel

Fig. 2 depicts the SPDs for Channel 1 (2,700K) and Channel 2 (6,800K), respectively. The radiant intensity of the SPD was relatively high in the range of about 580 to 680 nm for Channel 1, and relatively high in the range of about 440 to 470 nm for Channel 2. The illuminance of each channel is 832 lux and 918 lux, which represents the maximum illuminance of each channel. In addition, the CCT of each channel is 2,765K and 6,798K, and the SWR is 7.68% and 26.74%. This confirms that it is possible to control the lighting within the CCT range of 2,765 to 6,798K and SWR range of 7.68 to 26.74% by mixing the light sources of each channel.

2.2. *Calculate CCT and SWR by mixing ratio*

To generalize the correlation of the mixing ratio-CCT and mixing ratio-SWR of the test lighting, the CCT and SWR were calculated using the mixing ratio from the measured SPDs. For this purpose, the formula was derived based on Grassmann's color mixing law to mix the SPDs of each channel according to the set mixing ratio. From the mixed SPDs, the CCT and SWR were calculated. The CCT was calculated using McCamy's CCT formula [25-26]. SWR is calculated by dividing the integral in the short wavelength (380 to 480 nm) region by the integral in the visible light spectrum (380 to 780 nm) region.

$$SPD_{1+2}(\lambda) = SPD_{Max\_1}(\lambda)\times Ratio_{set} + SPD_{Max\_2}(\lambda)\times(1-Ratio_{set}),\ \lambda:\ Wavelength\ (nm) \tag{1}$$

$$Ratio_{real} = \frac{Illumiance_{Max\_1}\times Ratio_{set}}{Illumiance_{Max\_1}\times Ratio_{set} + Illumiance_{Max\_2}\times(1-Ratio_{set})} \tag{2}$$

In Eq. (1), SPD_{Max_1} and SPD_{Max_2} are the SPD at control level Max for each channel. In Eq. (2), $Illuminance_{Max\_1}$ and $Illuminance_{Max\_2}$ are the illuminances at the control level Max of each channel. The mixing ratio is defined as the illuminance of Channel 1 divided by the sum of the illuminance of Channels 1 and 2. For example, a mixing ratio of 0.5 means that the illuminance of Channel 1 and Channel 2 are equal. The mixing ratio is divided into a set mixing ratio ($Ratio_{set}$) and a real mixing ratio ($Ratio_{real}$). The reason for this is that if $Illuminance_{Max\_1}$ and $Illuminance_{Max\_2}$ are different, the $Ratio_{set}$ and $Ratio_{real}$ will also be different. To correlate the mixing ratio-CCT and mixing ratio-SWR, input values of 0, 0.1, 0.2, ..., 0.9, 1.0 into the $Ratio_{set}$ variable in Eq. (1) to obtain the mixed SPD. The CCT and SWR were calculated from the mixed SPDs. Table 1 shows the CCT and SWR by mixing ratio.

Table 1 CCT and SWR by mixing ratio

$Ratio_{set}$	$Ratio_{real}$	CCT (K)	SWR (%)
0	0	6,797.57	26.743
0.1	0.091489	6,158.71	25.047
0.2	0.184725	5,586.17	23.308
0.3	0.279758	5,073.78	21.527
0.4	0.376641	4,615.95	19.699
0.5	0.475429	4,207.68	17.825
0.6	0.576177	3,844.42	15.902
0.7	0.678946	3,522.05	13.928
0.8	0.783797	3,236.88	11.901
0.9	0.890792	2,985.53	9.819
1	1	2,764.95	7.680

In Table 1, $Ratio_{set}$ and $Ratio_{real}$ show different values by the ratio of $Illuminance_{Max\_1}$ (832 lux) and $Illuminance_{Max\_2}$ (918 lux) of the test lighting, which means that the luminous efficiency (illuminance efficiency) according to the applied current (control level) is different for each type of LED light source. CCT and SWR were confirmed to vary consistently in the range of 2,764 to 6,797K and 7.68 to 26.74% depending on the mixing ratio. Therefore, it is possible to derive highly correlated regression equations for $Ratio_{real}$-CCT and $Ratio_{real}$-SWR.

2.3. Implementation of a wavelength-based CCT control algorithm

A wavelength-based CCT control algorithm was implemented to reproduce the CCT and SWR of natural light. To improve the reproduction performance of SWR, the CCT range (±100K) of the 4-step MacAdam ellipse was set as the CCT tolerance of the algorithm. The algorithm calculates the appropriate mixing ratio for the target CCT and SWR, subsequently controlling the lighting by distributing the required illuminance by channel according to the calculated mixing ratio. For this purpose, the regression equations of mixing ratio-CCT and mixing ratio-SWR were derived using the data calculated in Section 2.2 and applied to the algorithm. Fig. 3 and Fig. 4 visualize the regression results of mixing ratio-CCT and mixing ratio-SWR as graphs and express the regression equation derived on each graph.

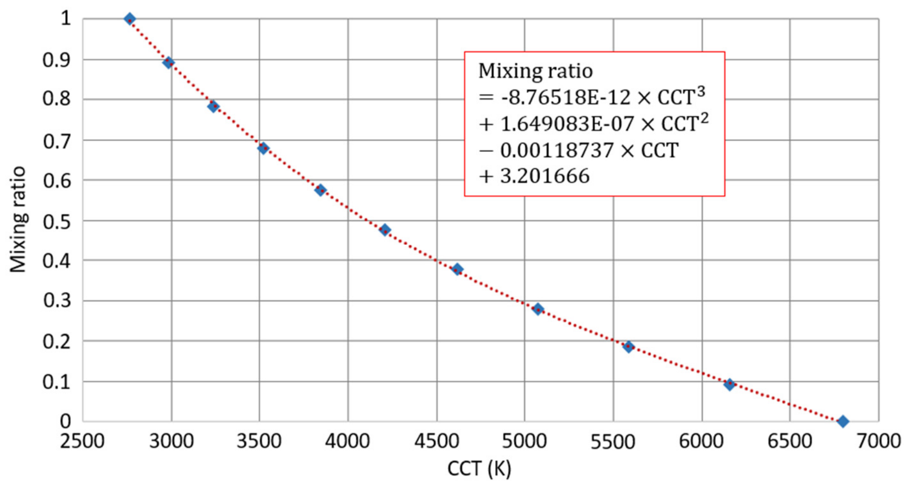

Fig. 3 Regression results of mixing ratio-CCT

Fig. 3 shows that the relationship between the mixing ratio and CCT is non-linear, while Fig. 4 shows that the relationship between the mixing ratio and SWR is linear. For both regression models, cubic regression analysis was applied to derive a regression equation with a high correlation coefficient. This resulted in strongly correlated regression equations with correlation coefficients between 0.9999 and 1. The derived regression equations were applied to the wavelength-based CCT control algorithm. Table 2 shows the pseudocode of the wavelength-based CCT control algorithm.

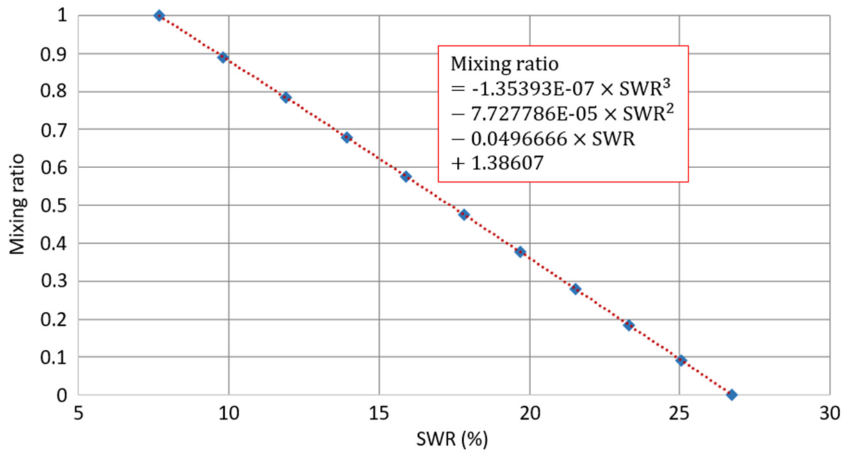

Fig. 4 Regression results of mixing ratio-SWR

Table 2 Pseudocode for wavelength-based CCT control algorithm

-	Algorithm
1	$Illuminance_{Target}, CCT_{Target}, SWR_{Target} = input(\ \ )$
2	$MixRatio = -1.35393E\text{-}07 \times SWR_{Target^3} - 7.727786E\text{-}05 \times SWR_{Target^2}$ $-0.0496666 \times SWR_{Target} + 1.38607$
3	$CCT_{Est} = CalculationEstimatedCCT(MixRatio)$
4	$If\ CCT_{Traget} - CCT_{Est} > 100$
5	$\quad CCT_{Traget} = CCT_{Traget} - 100$
6	$Else\ if\ CCT_{EST} - CCT_{Traget} > 100$
7	$\quad CCT_{Traget} = CCT_{Traget} + 100$
8	$Else$
9	$\quad CCT_{Traget} = CCT_{Est}$
10	$MixRatio = -8.76518E\text{-}12 \times CCT_{Target^3} + 1.649083E\text{-}07 \times CCT_{Target^2}$ $-0.00118737 \times CCT_{Target} + 3.201666$
11	$Illuminance_1 = Illuminance_{Traget} \times MixRatio$
12	$Illuminance_2 = Illuminance_{Traget} \times (1 - MixRatio)$
13	$Level_{Calc\_1} = RoundInteger\left(Illuminance_1 / Illuminance_{Max\_1} \times Level_{Max}\right)$
14	$Level_{Calc\_2} = RoundInteger\left(Illuminance_2 / Illuminance_{Max\_2} \times Level_{Max}\right)$
15	$LightingControl\left(Level_{Calc\_1}, Level_{Calc\_2}\right)$

The line-by-line description of the pseudocode in Table 2 is as follows. Line 1 inputs the target illuminance, CCT, and SWR ($lluminance_{Target}$, CCT_{Target}, and SWR_{Target}). Line 2 uses the regression equation in mixing ratio-SWR to calculate the mixing ratio (*MixRatio*) for the input SWR (SWR_{Target}). Line 3 uses the *CalculationEstimatedCCT* function to calculate the estimated CCT (CCT_{Est}) for the *MixRatio* calculated in Line 2. Lines 4 to 9 readjust CCT (CCT_{Target}) to not exceed 100K if the difference between the input CCT and the estimated is greater than 100K. Line 10 recalculates the mixing ratio (*MixRatio*) for CCT (CCT_{Target}) using the mixing ratio-CCT regression equation. Lines 11 to 12 distribute the target illuminance ($Illuminance_{Target}$) by channel based on the *MixRatio*. Lines 13 to 14 calculate the control levels ($Level_{Calc\_1}$, $Level_{Calc\_2}$) for each channel from the required illuminance ($Illuminance_1$, $Illuminance_2$) for each distributed channel. $Level_{Max}$ is 255, which is the maximum control level for the lighting. Finally, Line 15 controls the lighting with the *LightingControl* function.

3. Experiment and Evaluation

To experiment and evaluate the implemented algorithm, an experiment was conducted to reproduce the CCT and SWR circadian patterns of natural light. At the same time, an experiment was also conducted to reproduce natural light using a simple CCT control method, and the results of the two experiments were compared. The simple CCT control method is a simple algorithm that controls the CCT using only the regression of the mixing ratio-CCT in Fig. 3. The natural light data used in the experiment was collected by measuring once per minute from sunrise to sunset on October 24, 2020, using a spectrometer (CAS-140CT, instrument systems), and the data was collected on a clear day without clouds. The experiments were divided into A and B. In Experiment A, a wavelength-based color temperature control algorithm was used to reproduce natural light. In Experiment B, a simple color temperature control method was used to reproduce natural light. The illuminance was set to 500 lux according to the recommended indoor illuminance standard of KS A 3011 (300-600 lux). Fig. 5 and Fig. 6 visualize the reproduction results of CCT and SWR for Experiments A and B, respectively.

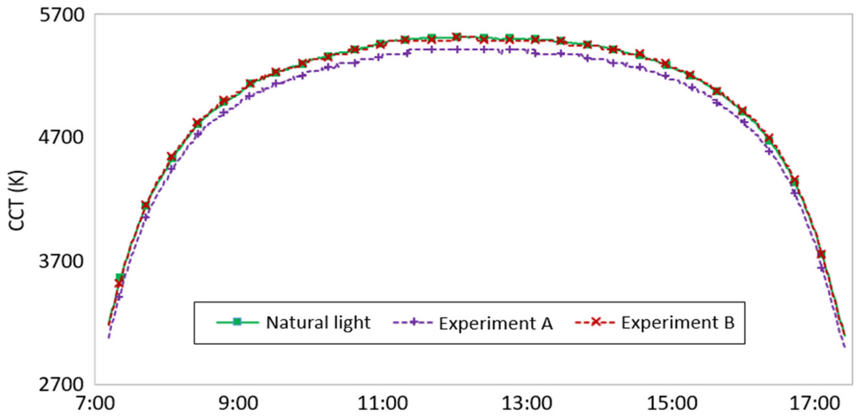

Fig. 5 CCT reproduction results for Experiments A and B

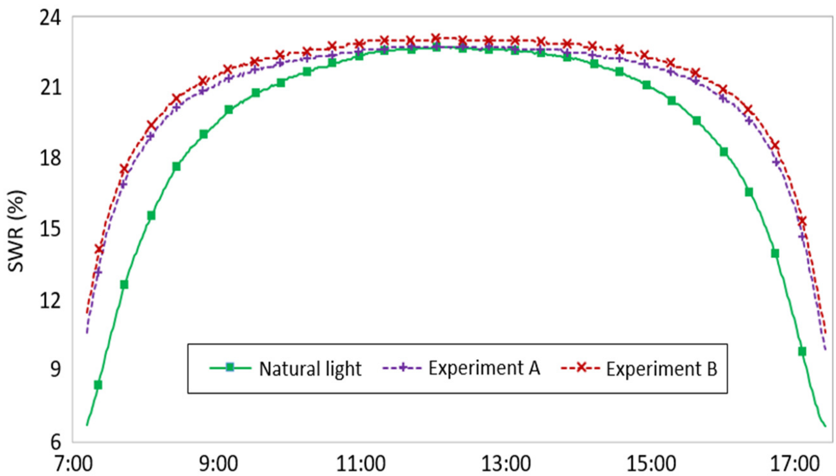

Fig. 6 SWR reproduction results for Experiments A and B

Fig. 5 and Fig. 6 show the reproduction results of CCT and SWR for the two experiments. The green line shows the data (target value) of natural light, and the purple and red lines show the data (reproduced value) of the reproduction results of Experiments A and B, respectively. The error (the absolute value of the difference between the target and reproduced values) was used to compare the resulting data from the two experiments. For Experiment A, the CCT of natural light was reproduced within an average error of 94.5K, and the reproduction error of SWR was on average 1.5% lower than that of Experiment B. For Experiment B, the CCT of natural light was reproduced within an average error of 10.9K, but the reproduction error of SWR was on average 1.88% higher than that of Experiment A. For the quantitative evaluation of the two experiments, the reproduction results of CCT and SWR in Fig. 5 and Fig. 6 were separated by time of day, and the average error was calculated. Table 3 summarizes the average errors for Illuminance, CCT, and SWR for Experiments A and B by the time of day.

The data in Table 3 shows the reproduction error of Illuminance, CCT, and SWR for each experiment, with smaller numbers indicating better reproduction performance. Looking at the illumination errors, it can be seen that Experiments A and B stuck to the set illumination of 500 lux in all time ranges. The average error in CCT for Experiment A was around 94.5K.

This is a relatively large error compared to the CCT average error of 10.9K in Experiment B, but it is a normal value considering the tolerance range (±100K) set to improve the reproducibility of SWR. For the SWR error, Experiment A was about 0.27 to 0.7% lower than Experiment B in all time ranges. The average SWR error over all time was 1.5% and 1.88% for each experiment, respectively, indicating that Experiment A had better SWR reproduction performance than Experiment B. Thus, the wavelength-based CCT control algorithm enabled CCT reproduction of natural light with improved reproduction performance of circadian rhythm-related SWR.

Table 3 Summary of average error by time for Experiments A and B

Time range	Experiment A (Avg. error)			Experiment B (Avg. error)		
	Illuminance (lux)	CCT (K)	SWR (%)	Illuminance (lux)	CCT (K)	SWR (%)
07h-08h	1.14	98.5	4.45	1.31	9.4	5.03
08h-09h	1.11	82.2	2.48	1.09	15.1	2.87
09h-10h	1.57	91.0	1.08	1.13	7.8	1.43
10h-11h	0.37	98.3	0.43	1.42	9.3	0.75
11h-12h	0.96	99.4	0.11	0.18	13.7	0.40
12h-13h	1.31	96.7	0.07	0.37	12.4	0.36
13h-14h	1.01	103.2	0.17	0.46	7.7	0.50
14h-15h	0.63	97.9	0.57	1.44	8.1	0.90
15h-16h	1.32	87.7	1.49	1.21	9.2	1.85
16h-17h	1.11	85.2	3.48	1.14	16.1	3.94
17h-18h	0.93	109.3	4.46	1.23	10.5	5.16
All time ranges	1.05	94.5	1.50	0.98	10.9	1.88

4. Conclusions

In this paper, a lighting control method is proposed to reproduce the CCT and SWR of natural light to maintain the human circadian rhythm. To this end, a wavelength-based CCT control algorithm that can operate on a two-channel LED light consisting of Warm White and Cool White was implemented and verified. To implement the proposed wavelength-based CCT control algorithm, a generalized method consisting of three steps was planned and realized. In step 1, the SPDs of each channel of the test lighting were identified through measurement experiments. In step 2, the CCT and SWR according to the mixing ratio of the channels were calculated from the measured SPDs of each channel. In step 3, regression analysis was used to derive the regression equations of mixing ratio-CCT and mixing ratio-SWR, and a wavelength-based CCT control algorithm was implemented. As a result of the natural light reproduction experiment for performance evaluation, it was confirmed that the CCT was 94.5K and the SWR was 1.5% within the average error range of natural light reproduction.

In the future, lighting control algorithms utilizing three or more multichannel LEDs will be studied to improve natural light reproduction performance. For multichannel LED lighting with three or more channels, a complex analysis of the mix of each light source is essential. To this end, advanced lighting control algorithms will be developed.

Conflicts of Interest

The authors declare no conflict of interest.

Acknowledgments

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