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Time-course analysis of change in display color-appearance based on ambient light change

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ABSTRACT
This study investigates the time course of changes in display color appearance according to changes in ambient lighting. Psychophysical experiments were conducted to observe brightness under lighting transitions in illuminance and the perceived white point under lighting transitions in correlated color temperatures. The result shows that significant change in the color appearance occurs immediately after ambient lighting changes. In addition, the initial change in color appearance depends on the lighting transition characteristics. The continuous change in color appearance was observed when ambient lighting was changed to brighter or lower CCT. On the other hand, a significant abrupt change at the initial stage of adaptation was observed when ambient lighting was changed to darker or higher CCT.

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KEYWORDS
Temporal color appearance change; Display color appearance; Chromatic adaptation; Luminance adaptation

1. Introduction

The human visual system adjusts its sensitivity to maintain an object's color appearance according to various viewing conditions [1]. Many studies have investigated the display color appearance according to ambient lighting [2–9]. Lighting from the display is perceived as dark under bright ambient lighting conditions [10]. The correlated color temperature (CCT) of the perceived white of display decreases as the CCT of ambient lighting decreases. Based on these studies, the display color can be adjusted to the optimal status in accordance with the illuminance and chromaticity of the ambient lighting detected through sensors. However, most studies on display color appearance have been conducted when people have fully adapted to ambient lighting. As mobile displays are widely used in our daily lives, displays are used more in dynamic environments, such as when passing through a tunnel, entering the room from the outside, and adjusting the color of the lighting etc. The display color appearance also changes depending on the adaptation state of the viewer to ambient lighting [11]. However, the process of display color appearance change based on the change in ambient light is not well researched.

In spite of the importance of studies on temporal appearance changes, only a few studies have investigated the time-course of the change in display color appearance according to the changes in ambient lighting. This is mainly due to the complexity of the experiments. Previous studies have measured the brightness and achromatic color appearance change over time using the detection threshold, method of adjustment, or forced-choice experiments. To reasonably investigate the change in color-appearance, the psychophysical task should be easy for non-experts and the learning effect must not occur.

In this study, two psychophysical experiments are conducted to track the changes in display color appearance over time as ambient light changes by focusing on the brightness and white point changes.

2. Experimental method for investigating the time course of changes in color appearance

2.1. Literature review

A few studies have investigated time-course changes in color perception based on two aspects of color appearance: brightness and white points. Poot *et al.* [12] studied the temporal process of luminance adaptation with detection threshold changes for a small light flash after background luminance is changed. They assumed that the detection threshold changed according to the adaptation to ambient lighting. The test pulse was presented for 10 ms at various times and the participants determined

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whether the stimulus was visible. Using the proportions of correct responses, the adaptation speed for luminance decrement or increment was estimated according to threshold changes over time.

To understand process of chromatic adaptation, most studies have used a method of adjustment to measure the adaptation state over time. Fairchild and Reniff measured the time course of color appearance changes during changes in six different chromaticity transitions [13]. In their study, three participants were asked to adjust a flashed test stimulus to preserve their achromatic appearance after various durations of adaptation from daylight to incandescent lighting. The stimulus was presented for a 0.1 s once per second. As the result, the color appearance was changed along a line between daylight (D65) and adapting chromaticity in the CIE chromaticity diagram. The participants were trained to be familiar with evaluating color appearance within a few seconds. Rinner and Gegenfurtner explored the temporal characteristics of chromatic adaptation when the background color of a cathode ray tube (CRT) screen changed along the red–green and yellow–blue axes [14]. One second after the background color was changed, the stimulus was briefly presented for 83 ms once every 5 s. Participants adjusted the chromaticity of the stimulus to appear neutral. They were able to respond to chromatic changes within 5 s. The color of the stimulus was controlled along the same color axis to reduce the complexity of the task. Later, Shevell investigated the time course of chromatic adaptation when the R phosphor of the CRT was turned on at 0.80 log cd/m^2 [15]. The participants controlled the G photoreceptor to obtain an achromatic color appearance once every 30 s. The participants were instructed to perform the task as rapidly as possible. Recently, Spieringhs *et al.* used two methods to investigate the time course of chromatic adaptation: method of adjustment and forced-choice using constant stimuli [16]. To investigate the process of chromatic adaptation under a step change in the chromaticity of lighting, participants were asked to adjust the stimulus until it appeared neutral along the corresponding chromaticity path. The time set for adjusting the color of the stimulus was not limited, and the test patch was turned dark for 20 s between each evaluation. To compare the speed of chromatic adaptation according to the speed of lighting change, participants evaluated the color of the constant stimuli as either yellow or blue every 5 s. This study reported that the experimental result is influenced by the different psychophysical methods. Following Spieringhs' study, Yoon *et al.* compared two methods used previously, method of adjustment and forced choice, to investigate the proper experimental method to investigate the color-appearance changes under the changing light [17]. Significant differences were observed between the two methods. Method of adjustment was difficult for non-expert participants to find the exact achromatic color within a brief period of time. The duration of the stimulus presentation was too short to adjust the color appearance of the stimulus. In addition, the after-image effect was observed. However, the forced-choice experiment showed a more consistent result, and the color appearance converged to a certain level as the adaptation proceeded. Avoiding the learning effect induced by repetitive evaluations and the range effect of stimuli are the important details to note in the forced choice experiment.

2.2. Experimental method

Based on the previous research, our study adopted the method of presenting the stimulus for a short period at a specific time and measuring the color appearance using a simple task. Figure 1 illustrates the concept of the experimental method. There are two main characteristics. The first involves tracking the color appearance of the display at each specific moment by presenting stimuli for a short time at regular intervals.

As shown in Figure 1(a), the stimulus was presented once every t_d seconds. To avoid the after-image effect and minimize adaptation to the light from the display, the presentation period of the display image was controlled to be minimal and regular. After presenting the stimulus for Δt seconds, a black screen appeared before the next stimulus. The participants evaluated the color of the stimulus within t_d seconds. The presentation period and psychophysical experimental task depended on the type of appearance to be measured. The period was determined according to the pilot test to make the evaluation relatively easy.

The second characteristic involves the method for gathering responses to all stimuli at a specific time. To track the change in color appearance over time, all stimuli had to be evaluated regularly. Repetitive evaluations of the same stimulus can cause a learning effect. Thus, this study utilized a Latin square design for the sequence of stimuli to avoid the learning effect. A Latin square design in an n×n array was filled with n different elements [18]. In the Latin square design, each stimulus exists only once in each row and column. Figure 1(b) shows an example of stimulus presentation with a Latin square design for 3 stimuli. The rows indicate the order for each trial over time. The columns, notated as t_0 and $t_0 + t_d$, indicate the specific moment of each trial. By repeating the evaluations according to all rows, the color appearance of all stimuli could be tracked over time. The overall

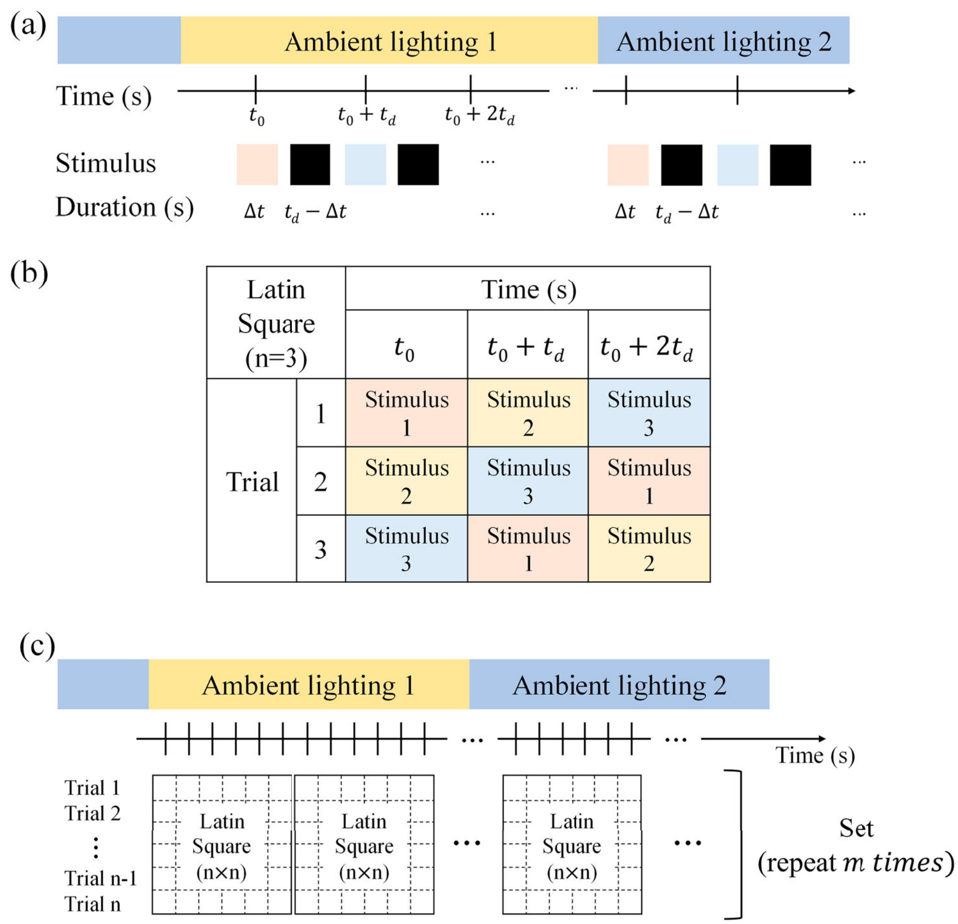

Figure 1. The experimental method. (a) regular presentation of stimuli (b) Latin square design example (c) Latin square design utilized for time course experiment.

experimental timeline is shown in Figure 1(c). The Latin squares are also connected according to time. If the number of stimuli was n, one set is composed of n trials. In the case of the forced-choice experiment, the evaluations of all stimuli over time were repeated m times to collect the proportion of responses. Therefore, n×m trials were needed.

In this study, two psychophysical experiments approved by the Institutional Review Board were conducted under changing ambient lighting conditions. In the first experiment, the change in display brightness was investigated according to the change in ambient lighting intensity. During the lighting transition, participants evaluated the brightness of the display using the magnitude estimation method. In the second experiment, the perceived display white-point change was investigated according to the change in ambient lighting CCTs. Participants evaluated the hue of the display as either yellow or blue. Since the main goal of our experiments was to track the changes in color appearance over time, abrupt and large ambient lighting changes were applied to observe the changes in color appearance more clearly.

3. Change in brightness experiment

3.1. Experimental setting

3.1.1. Experimental environment

Ambient lighting was obtained using a light-emitting diode (LED) lighting booth (THOUSLITE LED cube) in a dark room. The booth with dimensions of 500 mm (width) × 600 mm (depth) × 600 mm (height) was located on a table at a height of 81 cm. Various ambient lighting conditions were produced by controlling the intensity of 15 LED channels. As shown in Figure 2, the participants were located 80 cm from the display. A viewing table was placed at the center of the lighting booth, with a liquid-crystal display (LCD) placed on it at 60°. The participants adapted to ambient lighting by looking at the entire interior of the lighting booth. The experimental stimuli were presented on a Samsung Galaxy S7 device with a full-screen image. The display had a screen diagonal of 129.2 mm and a resolution of 2560 × 1440 pixels. The participants viewed the display placed perpendicularly to their line of sight with a field of view (FOV) of approximately 4.54 × 8.07°.

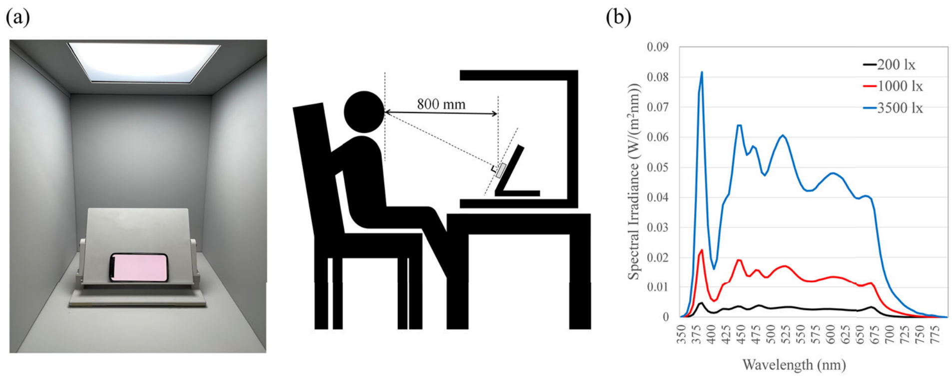

Figure 2. (a) Experimental setting and (b) SPD of light conditions.

Table 1. Luminance of the stimuli in experiment 1.

	Target			Trick					
Y(cd/m^2) #	1	2	3	1	2	3	4	5	6
Dark room	20.1	91.2	159.3	5.7	20.1	48.8	91.2	107.2	192.0
200 lx	21.5	91.6	160.7	7.1	21.5	50.0	92.4	108.6	193.4
1000 lx	24.1	95.0	164.0	9.8	24.1	52.7	95.0	110.9	195.9
3500 lx	34.7	105.0	172.8	20.4	34.7	63.2	105.0	121.1	205.6

3.1.2. Ambient lighting

Lighting with three levels of illuminance, 200, 1000, and 3500 lx, was provided. The THOUSLITE PS spectrometer measured the spectral power distribution (SPD) of the light at the center of the bottom of the lighting booth. Colorimetric coordinates were calculated using a CIE 1931 2° standard colorimetric observer. The luminance of the center of the wall of the lighting booth was measured using a spectroradiometer (CS-2000) at 21.71, 109.60, and 380.50 cd/m^2 under 200, 1000, and 3500 lx lighting, respectively, while the CCT was 6451 ± 34 K. These illuminances were darker, similar, and brighter than the luminance of reference stimulus. The experiment was divided into two sessions: illuminance transition between 200 and 3500 lx (session1) and 1000 and 3500 lx (session2) to investigate the effect of illuminance difference on changes in brightness perception. In each session, the lighting changed from dark to bright and bright to dark. Therefore, four lighting conversion conditions were used.

3.1.3. Stimuli

Three luminance levels of gray images were used as stimuli to track the change in brightness over time. If only three stimuli are presented repeatedly, it would be easy for the observers to distinguish them as well as memorize their previous responses. Therefore, a total of seven stimuli were selected and divided into target and trick groups. All stimuli had similar chromaticities (0.2938 ± 0.0066, 0.3276 ± 0.0073 in CIE 1931 xy chromaticity diagram) with different luminance levels.

Table 1 shows the luminance levels of stimuli measured for each lighting condition. In a previous study, the stimulus was presented once every 5 s [16,17]. The three target stimuli were presented once every 10 s, according to the Latin square design. Between the target stimuli, the trick stimuli were presented in random order. The target and trick stimuli alternately appeared once every 5 s for 1 s. Therefore, t_d and Δt in Figure 1 were 5 s and a second, respectively.

3.1.4. Psychophysical procedure

A psychophysical experiment was conducted to investigate how the display brightness varies with the change in illuminance of ambient lighting. Before starting the experiments, the participants read information about the experimental procedure and tasks before subsequently signing an informed consent form.

Magnitude estimation was used to quantitatively collect the responses of the display brightness. Participants responded to the brightness of the stimuli by comparing it to the reference stimulus. A stimulus with moderate luminance was used as a reference stimulus for assessment. The brightness of the reference stimulus was set to 50 points. The brightness of black was 0 points, and the maximum value was not limited. If the stimulus was darker than the reference, the response was less than 50. If it was brighter, the response was a number greater than 50. As the reference stimulus was not shown during the experiment, the participants were required to evaluate brightness based on their memory.

For each session, ambient lighting was brightened or darkened. The initial lighting was randomly assigned and the participants adapted to it for 2 min. Before starting the evaluation, the participants remembered the brightness of the reference stimulus under initial lighting. Then, they evaluated the brightness stimulus, which was presented once every 5 s. As the target and trick stimuli were alternated, the brightness responses of the target stimuli were collected 24 times for 4 min under the initial lighting. After the evaluations under the initial lighting, ambient lighting conditions were changed. Immediately after the lighting change, the participants conducted evaluations for 4 min. They evaluated the brightness of the stimuli based on the brightness of the reference stimuli under initial lighting. After the evaluations were completed under both ambient lighting conditions, the lighting conversion was repeated three times to track the brightness change over the time of all target stimuli. During the three trials, the order of the presentation of stimuli was based on the Latin square design. This procedure was repeated for other lighting conversions, which were changed in the opposite direction. Therefore, the experiment took 60 min in total, with two types of lighting conversions for each session.

3.1.5. Participants

There were 16 and 15 participants (21 males and 10 females) aged between 20 and 25 years for each session. They were between-subject groups and had normal color vision, as determined using the Ishihara test. The participants did not know the purpose of the study and were non-professionals in the field of study. They were trained on brightness using a Munsell student color book [20].

3.2. Experimental result

3.2.1. Observer variability

The reliability and reproducibility of the experimental data were verified using the coefficient of variation (CV) to confirm the observer's performance. The CV value equation is as follows:

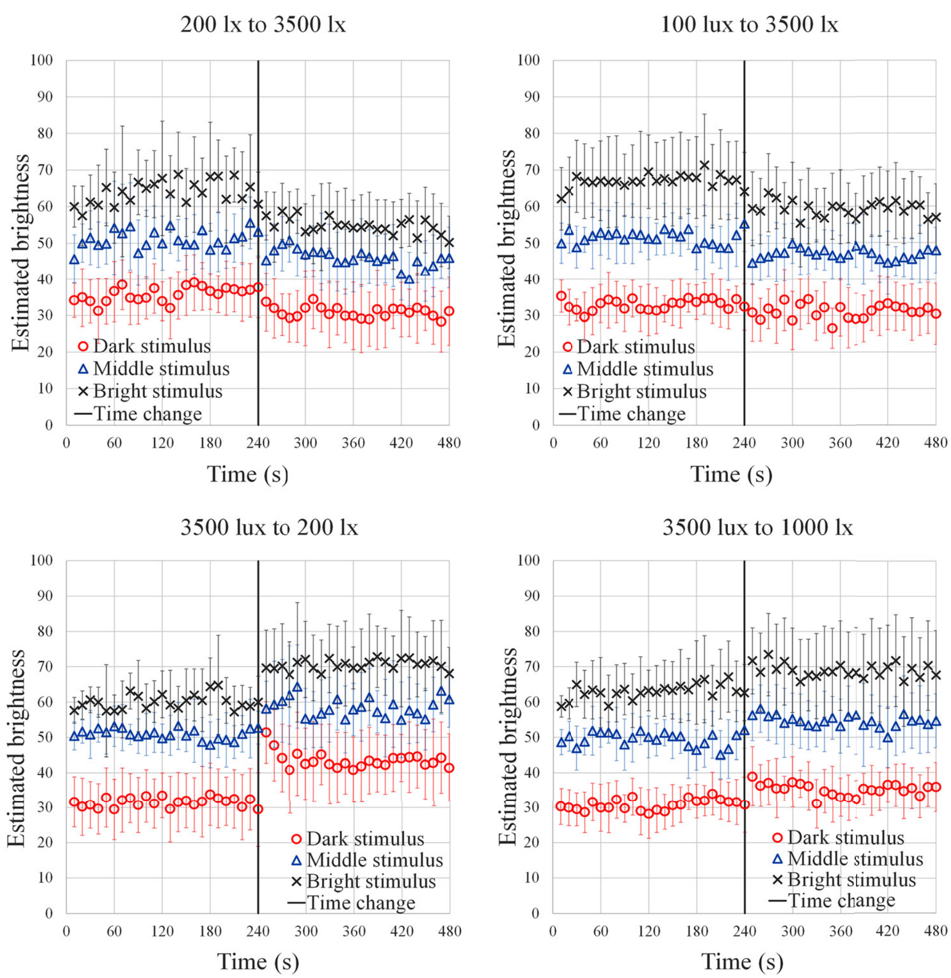

Figure 3. Estimated brightness change over time.

$$CV = 100\left(\frac{\sum (x_i - y_i)^2}{n}\right)\Big/\bar{y}, \quad (1)$$

where x and y indicate the response of each trial and the average of all trials, respectively; i is the number of evaluations in the trial in which n evaluations are performed. The responses under initial lighting gathered after adaptation for 2 min were used to calculate the CV value. A larger CV value indicates less repeatability because the standard deviation is larger than the mean. The averages of the CV values were 10.2% and 8% while the standard deviations were 2.6 and 2.3 for each session, respectively. These values are stable enough compared to previous studies [2,6,7].

To confirm the reproducibility of the between-subject groups, responses under 3500 lx lighting conditions in both sessions were compared. Although there were different subject groups in the two sessions, the estimated display brightness under 3500 lx was not significantly different as the average of the CV values of each stimulus was 0.17%.

3.2.2. Brightness change under lighting conversion in illuminance

The brightness of the display under the lighting transition was analyzed by averaging the participants' responses at each moment. Figure 3 shows the average brightness of the three luminance levels of the target stimuli. Among the three luminance levels of the stimuli, the middle stimulus had the same intensity as the reference stimulus, which was assigned as 50 points of brightness. The estimated brightness of the second stimulus under initial lighting was approximately 50 points in all sessions. The responses under the initial lighting were also stable. This means that the participants maintained the criteria for brightness evaluation.

As ambient lighting became brighter, the luminance of the stimuli slightly increased as the amount of light reflected on the display screen increased. Nevertheless, the estimated brightness was lower under brighter lighting than under dimmer lighting. On the other hand, the estimated brightness increased as the ambient lighting became darker. This result correlates with previous studies [2,3,6,9].

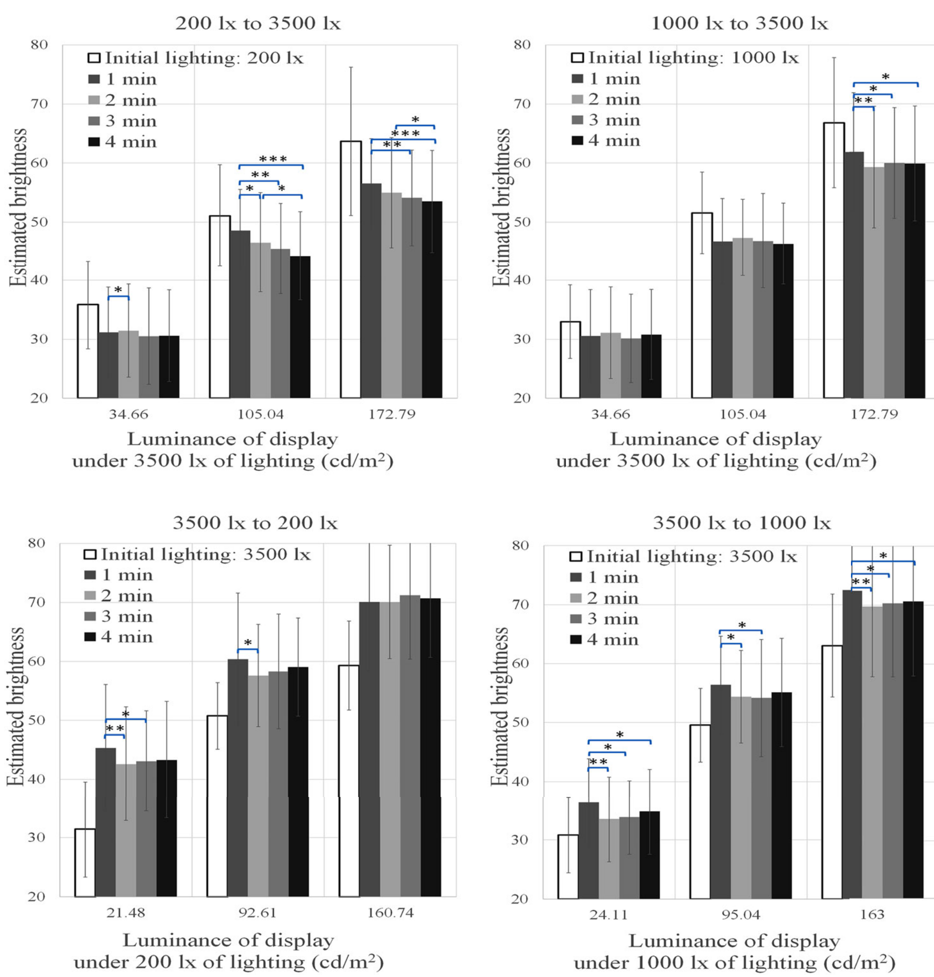

Figure 4. Brightness change over time under lighting transition in illuminance.

When the ambient lighting was changed between two lighting conditions, the estimated brightness varied over time. According to Figure 3, significant change in the estimated brightness occurred immediately after the lighting transition and then converged to a certain level. To observe this phenomenon statistically, the estimated brightness was averaged in one-minute intervals. Figure 4 shows the brightness change according to the luminance of the stimuli under four lighting transitions. The first bar indicates the average response under initial lighting. The following 4 bars indicate the estimated brightness for 4 min after the lighting transition. Therefore, the 5 bars show the change in brightness between the two lighting conditions. The significant differences in brightness over time were analyzed through the paired *t*-test. Results showed that the difference between the brightness in the first minute and that in the other minutes was significant. The estimated brightness for one minute as soon as the lighting changed was 2%–10% higher than the converged brightness. Although the display became darker or brighter depending on the lighting transition, a deviation within the first minute was observed regardless of the experimental conditions. It caused different trends in the color-appearance changes depending on the adapting luminance changes. When ambient lighting was brightened from 200 or 1000 lx to 3500 lx, the perception of the stimulus was smoothly darkened. However, when the lighting was darkened from 3500 lx to 200 or 1000 lx, the stimulus was instantly perceived as brighter and stabilized to a certain level.

4. Perceived display white point change experiment

4.1. Experimental method

The experimental environment was the same as that used in the previous authors' study [17].

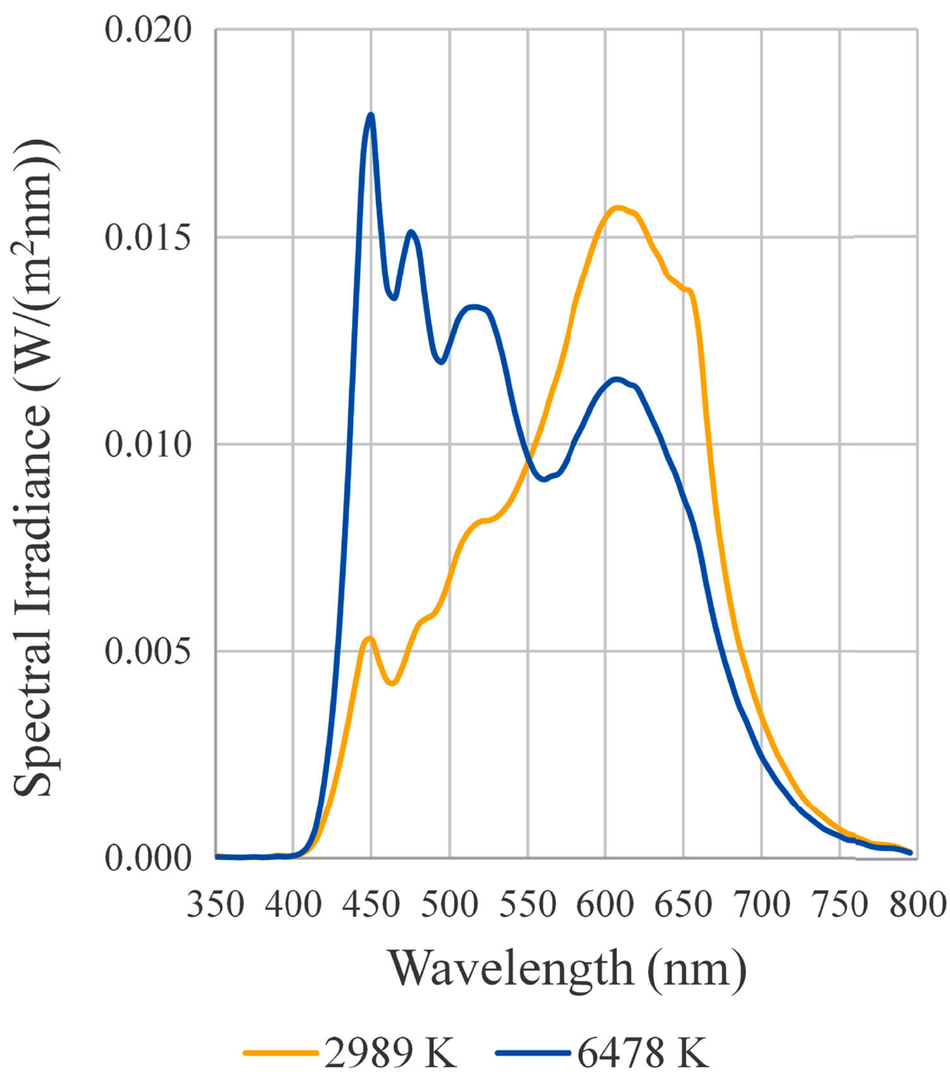

Figure 5. SPD of two lighting conditions.

4.1.1. Ambient lighting

Two ambient lighting conditions had two levels of CCTs, 2989 and 6478 K, with chromaticity at the Planckian locus ($D_{uv} = 0.000$) and the same illuminance level of 800 ± 3 lx. Figure 5 shows the SPD of two lighting conditions. The luminance level of the mid-gray paper was 80.3 ± 0.3 cd/m^2 under both ambient lighting conditions, while CIE xy chromaticities were (0.446, 0.415) under 2989 K and (0.319, 0.344) under 6478 K.

4.1.2. Stimuli

The stimuli were displayed on an iPad Mini LCD. The size of the display was 200.7 mm in the diagonal direction with a resolution of 2048 × 1536 pixels. The display was covered with mid-gray paper, except for a 2 cm × 2 cm square hole in the center. Thus, the participants viewed the display placed perpendicularly to their line of sight with a FOV of approximately 2°. The maximum luminance of the display was 512.3 cd/m^2.

Since the white point differs from person to person, the six stimuli for the experiment were determined individually. To find the white points individually, a prior test was conducted with 10 stimuli. The CCTs of the 10 stimuli were distributed from 4000 K to 6150 K and from 4800 K to 8600 K for 3000 and 6500 K lighting, respectively. The D_{uv} values of the test colors ranged from 0 to 0.0045. The average D_{uv} value was 0.0020. The luminance level of all the test colors was 203 ± 5 cd/m^2.

4.1.3. Psychophysical procedure

Before the start of the experiments, the participants read pertinent information about the experimental procedure and tasks before signing an informed consent form. The participants practiced the task by evaluating the color of the stimuli.

The participants were asked to make a forced-choice judgment regarding the color appearance of the stimulus. They identified the hue of the stimuli, i.e. whether the stimulus was perceived as yellow or blue, by pressing either the left or right arrow keys on the keypad.

A prior experiment was conducted to select the six stimuli for each participant. For both lighting conditions, the participants adapted to the environment for 2 min. Then, a stimulus was randomly presented once every 5 s for 0.5 s. The participants evaluated 10 stimuli with 10 repetitions for each lighting. The proportion of 'Blue' responses to the 10 stimuli was fitted to the logistic psychometric function. The perceived white point was

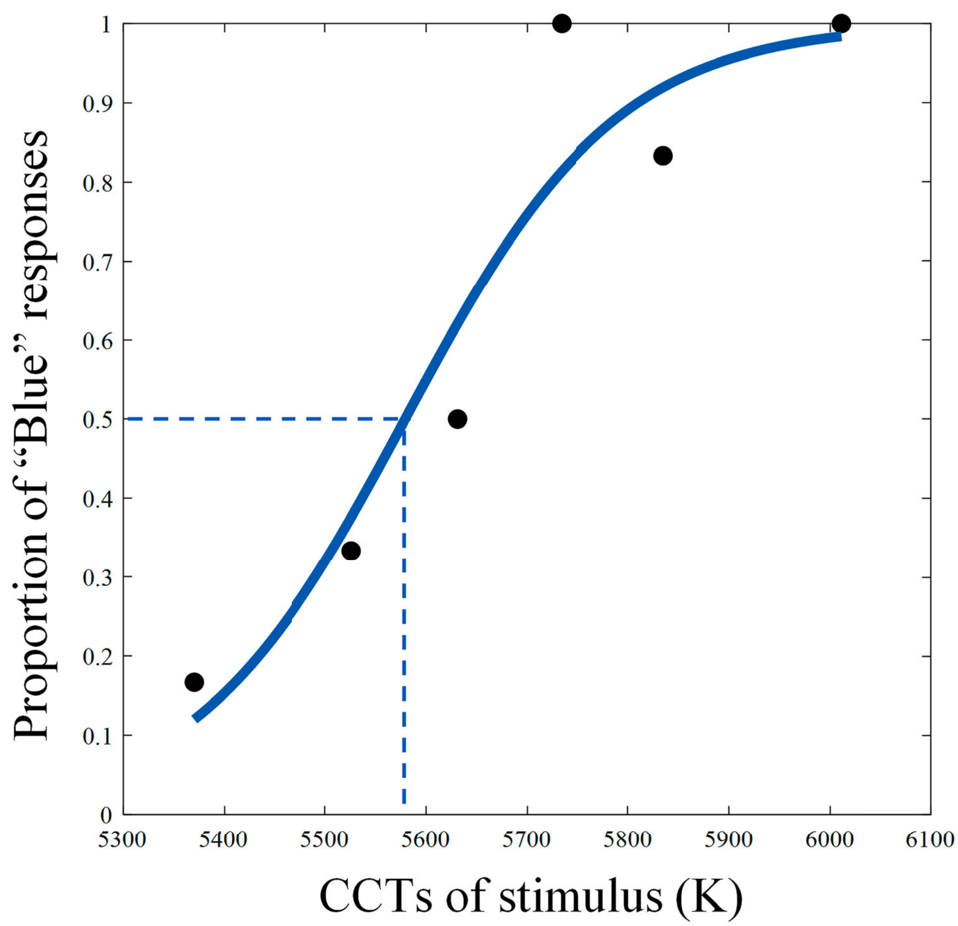

Figure 6. Example of psychometric function fitting to estimate the perceived white point for each moment.

estimated as 50% of the 'Blue' proportion according to the psychometric function. The CCTs of the 6 stimuli for the main experiment were equally spaced between two estimated white points.

In the main experiment, the evaluation was conducted under two lighting transitions. Two lightings were alternated within a 4 min cycle. For example, when the experiment started under 6500 K lighting, 3000 K lighting immediately followed for 2 min and then changed to 6500 K again for 2 min.

First, the initial lighting was randomly assigned and participants adapted to the initial lighting for 2 min. The lighting was then changed to the other, and the stimulus was immediately presented. The participants evaluated the hue of the stimulus, which was presented once every 5 s for 0.5 s. After 2 min, the lighting was changed again to the initial lighting. For each experiment set, twelve lighting transitions were conducted. With six repetitions of each lighting, all stimuli were presented once every 5 s in the order based on the Latin square design. In addition, the proportion was estimated by repeating the set six times.

4.1.4. Participants

Twelve participants (7 males and 5 females) aged between 19 and 25 years participated in this experiment. They had normal color vision, based on the Ishihara test, and did not have any knowledge of the study. The experiment was performed for 3 days to reduce fatigue. The task of finding the estimated white point under each lighting condition was conducted on the first day, and 6 sets of the experiment were conducted over 2 days.

4.2. Experimental result

The color appearance was investigated through the proportion of 'Blue' responses. The participants' responses about the six stimuli at a specific moment were fitted to a logistic psychometric function using (MATLAB PAL_PFML_Fit function). The maximum likelihood criterion was used to define the best-fitting psychometric function that is most likely to replicate the experimental result [19]. The logistic function is given as:

$$F_L(x;\alpha,\beta) = \frac{1}{1+exp(-\beta(x-\alpha))} \tag{2}$$

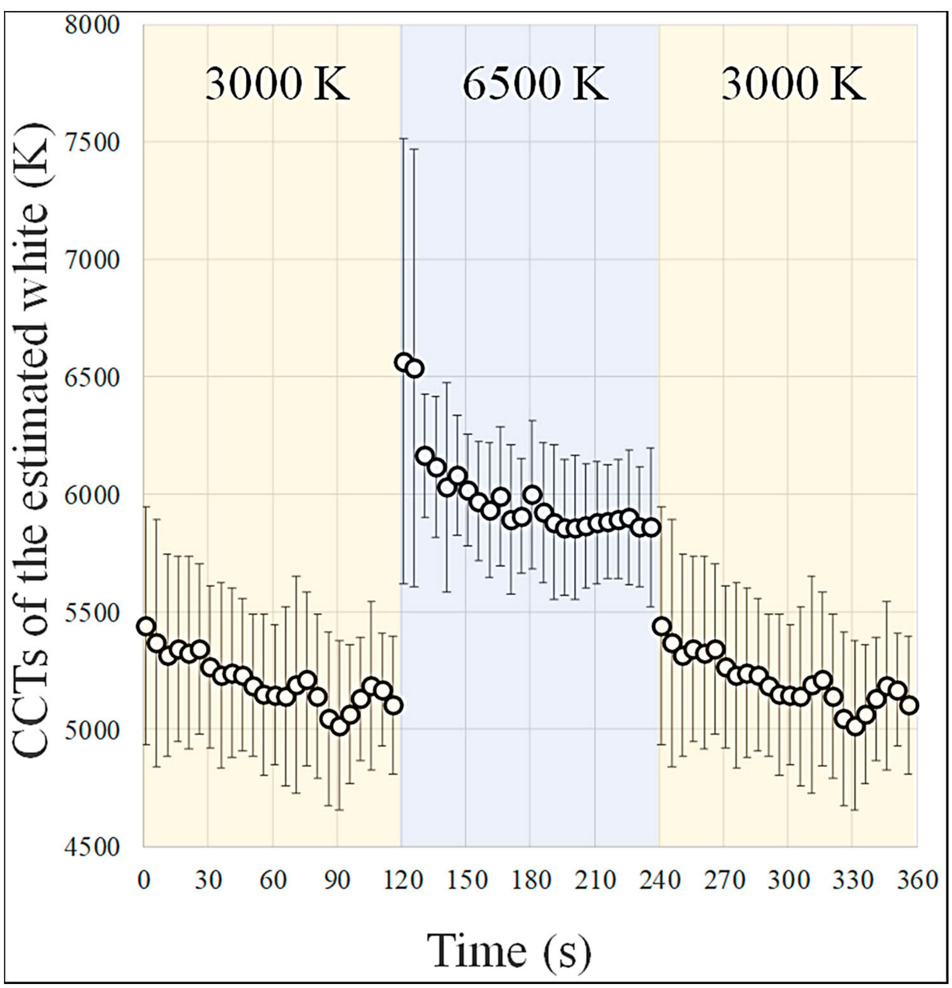

Figure 7. CCTs of estimated white change over time when lighting is changed between 6500 and 3000 K.

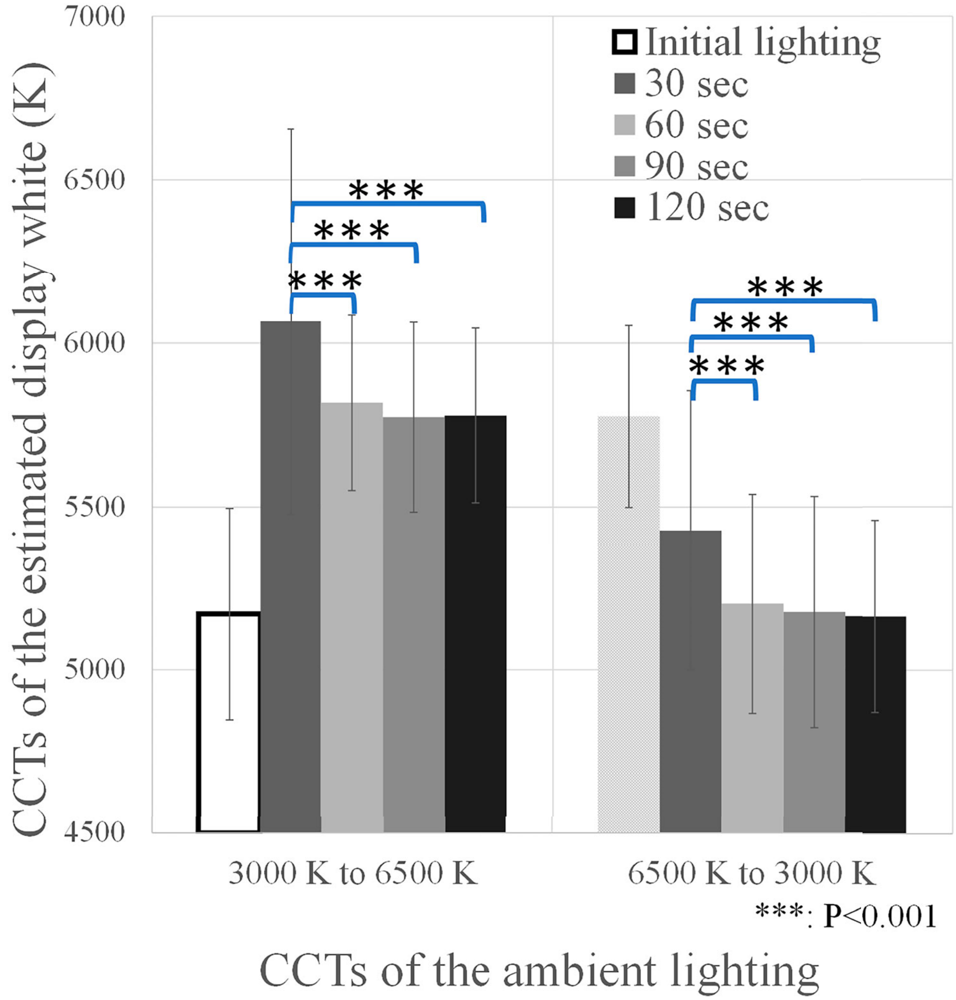

Figure 8. CCTs of the estimated white change over time under lighting transition in chromaticity.

with $x \in (-\infty, +\infty)$, $\alpha \in (-\infty, +\infty)$, $\beta \in (0, +\infty)$. Parameter α corresponds to the threshold which indicates the white point corresponding to 50% of the 'Blue' proportion ($F_L(x = \alpha; \alpha, \beta) = 0.5$). Therefore, 50% of the 'Blue' proportion was estimated as the white point, which means an indistinguishable point in the hue judgment. Parameter β determines the slope of the psychometric function. Figure 6 shows an example of the proportion of 'Blue' responses of six stimuli and the fitted psychometric function when the 9th participant adapted to 3000 K lighting for a second. The white point was estimated once every 5 s for 2 min individually under each lighting condition. The estimated white points of the same moment were subsequently averaged. We estimated the average of 24 white points during 120 s under each lighting condition. The data points in the two graphs in Figure 7 represent the estimated white points over time under the two lighting transitions. The white point changed significantly at an earlier time and converged to a stable level after a certain period. The standard deviation was high on the first trial under 6500K lighting. After a few seconds, the color appearance converged to a certain level. As the CCT of ambient lighting became higher, the higher display CCTs were assumed to be white points. The average estimated display white points under 3000 and 6500 K lighting conditions were 5171 ± 324 K and 5776 ± 277 K, respectively. The results of this experiment corresponded with those of earlier studies [4–6].

Figure 8 shows the statistical evidence of the initial change by averaging the CCTs of the estimated white point in 30 s intervals. The significantly different changes during the initial 30 s were confirmed by the paired t-test. The change in the estimated white point differed depending on the lighting transition. When the lighting was changed from 3000 K to 6500 K, a significant increase in the CCTs of the estimated display white point occurred immediately after the lighting changes. Subsequently, it gradually decreased and converged to a certain level. When the lighting was changed from 6500 K to 3000 K, the CCTs of white smoothly decreased from the white point at 6500 K and converged to a stable level after a few seconds.

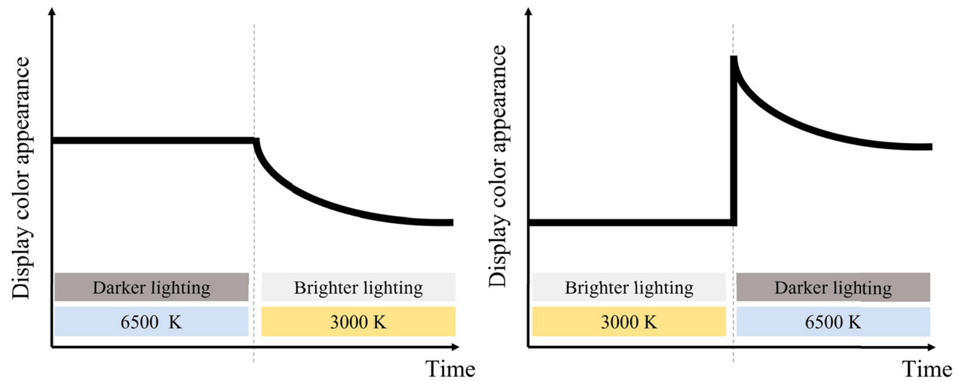

Figure 9. Schematic illustration.

5. Discussion

Based on the experimental results, it was found that the common characteristics of color appearance change in two types of lighting transitions. Figure 9 shows a schematic illustration of the temporal color appearance change process according to lighting conversion. In both lighting transitions in illuminance and chromaticity, two different changes in color appearance were observed immediately after the lighting transition. A large increment in brightness and CCTs of the estimated display white point was observed instantly after the lighting became darker or bluer. However, no abrupt change in color appearance was observed immediately after the lighting became brighter or yellower.

Since only a few phases of the environment were investigated, this study has a limitation in modeling color perception changes according to adaptation. To model the changes in perception, the experimental conditions should be expanded. These experimental data should be useful for future research on modeling color appearance changes over time in various environments.

6. Conclusion

This study investigates the time course of display color-appearance change according to ambient lighting change. The stimuli on the display were presented for a short time at regular intervals. Two experiments, one on brightness and the other on perceived display white points, were conducted. The results show that significant changes in the color appearance occur immediately after the ambient lighting changes. In addition, the initial change in color appearance depends on the lighting transition characteristics. When ambient lighting was changed to brighter lighting or lower CCT, the brightness and estimated white point continuously changed immediately after the lighting transition. However, a significant abrupt change was observed at the initial stage of adaptation when ambient lighting was changed to darker lighting or higher CCT.

Since this study only covers limited experimental conditions, additional intensive research under more diverse lighting environments is required to establish the modeling of human perception changes in a dynamic environment.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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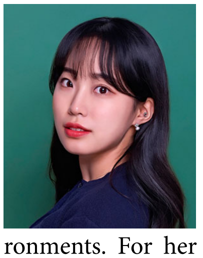
Notes on contributors



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Youngshin Kwak received her BSc and MSc degrees in physics from Ewha Womans University, South Korea. After completing her PhD study at the Colour & Imaging Institute, University of Derby, UK, she worked for SAIT, South Korea. Since Feb. 2009, she is working as an associate professor at the Biomedical Engineering Department of Ulsan National Institute of Science and Technology (UNIST), South Korea. Her main research interests include color appearance model and image quality.

Hyosun Kim received a BS degree in psychology and MS and PhD degrees in cognitive science from Yonsei University, Seoul, South Korea in 1997, 2003, and 2012, respectively. From 2003 to 2007, she worked as a research assistant at the Institute of Cognitive Science in Yonsei University. She is currently working at Samsung Display in Yongin, South Korea. Her research interests include human perception and eye fatigue.

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