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Effect of viewing environments on perceived display neutral point

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Abstract: In this study, the influences of ambient chromaticity, ambient luminance, and display luminance on the perceived neutral point of a display were systematically investigated using 25 experimental settings. The results show that the surround ratio, i.e., the ratio of the ambient luminance to the display luminance, had a greater effect on the display neutral point perception than the absolute intensity of each factor. As the surround ratio decreased, indicating that the display luminance was higher than the ambient luminance, the perceived display neutral point changed from the adapted white to the neutral point in the darkroom condition (corresponding to a surround ratio of zero) at approximately 7,200 K. When the surround ratio exceeded 1.0, the neutral point of the display gradually shifted toward specific levels. The correlated color temperatures of the perceived display neutral points converged to 5,000 and 5,900 K under ambient lighting conditions of 3,000 and 5,000 K, respectively.

1. Introduction

The display white point refers to the chromaticity of white represented on a display. Setting the display white point is crucial for enhancing image quality because it influences display color appearance, including colorfulness, hue, naturalness, and Ref. [1–4]. The display white point should be set to chromaticity such that it appears as a neutral color in the environment to improve the image quality [5]. The neutral color changes according to the viewing conditions based on chromatic adaptation [6]. Because existing chromatic adaptation transform (CAT) models consider only the luminance of ambient lighting to predict the degree of chromatic adaptation, predicting the display neutral point using the CAT model is challenging [7,8].

Numerous studies have investigated neutral points in various display-viewing environments. Kwak et al. [9] and Li et al. [10] examined the effect of ambient lighting chromaticity on the preferred display white point, which represents the desired chromaticity of the display white point. Their findings revealed that the display white points should be set to higher correlated color temperature (CCTs) with higher CCTs for ambient lighting. Similarly, in environments with lower CCTs, the display white points should be set at the lower CCTs. Furthermore, other studies have observed a correlation between the ambient luminance and chromaticity of the preferred display white point [11,12]. When the ambient chromaticity is constant, the preferred display white point moves closer to the ambient chromaticity as the ambient luminance increases [13–15]. This effect became more pronounced under low ambient lighting CCTs. However, a large chromaticity difference between the preferred display white point and ambient chromaticity was observed at low CCTs of ambient lighting, despite a sufficiently high ambient luminance.

The white points of the display were also investigated based on the viewing mode of the display. Zhai and Luo analyzed chromatic adaptation to ambient lighting via neutral white matches in different viewing media, including surface and self-luminous colors [16]. They found that the neutral white point of the surface colors was closer to the ambient chromaticity than that of self-luminous colors. Conversely, previous research has shown that the display color can be

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perceived as either self-luminous or surface, depending on the lightness of the display [17,18]. Moreover, Wei and Chen observed that the whitest chromaticity of a display is closer to the ambient conditions when the ambient luminance is considerably high, similar to the result for reflective surface colors [14]. Therefore, they concluded that the effect of the viewing media on the display white point is caused by the viewing mode, which is influenced by changes in the ambient luminance.

Previous studies have observed display neutral points under diverse conditions. Although they emphasized the significant impact of environmental factors on the display neutrality point, comprehensive research is still lacking. Therefore, our study aimed to explore the relationship between these parameters and the display neutral points. Specifically, we systematically examine the effects of ambient chromaticity, ambient luminance, and display luminance on the white point of the display. Our experimental design allows the simultaneous investigation of the influence of both the relative and absolute luminance of ambient lighting and display.

When our eyes observe a display within its surrounding environment, we adapt to both the light emitted from the display and ambient lighting conditions [19,20]. This effect was particularly pronounced when the display was brighter than the surrounding environment [14]. Because of the rapid adaptation process [21–24], restricting the time required to represent the stimulus on the display is critical for accurately investigating the neutral point in relation to adaptation to ambient lighting. However, most previous studies used an adjustment method to examine the neutral point of a display [14–16]. The participants were instructed to adjust the chromaticity of the stimulus until it appeared neutral. This methodology has the potential to induce adaptation to display light. To prevent biases arising from adaptation to the display light, we adopted short stimulus presentations and a forced-choice method for concise responses. The neutral point was estimated based on the hue data of the stimuli, which was demonstrated as a reliable method in our previous study [25].

2. Experimental method

Table 1 summarizes the 25 experimental settings used in this study, which were varied based on ambient chromaticity, ambient luminance, and display luminance. How much brighter the ambient lighting is compared to the display is represented by the surround ratio (S_R), which is the ratio of the ambient luminance to the display luminance. For each ambient chromaticity condition, several levels of surround ratios were prepared to achieve an identical ratio between ambient and display luminance with different levels of ambient luminance and combinations with different ratios but the same level of ambient luminance. Further details on the ambient lighting and stimuli are provided later in this paper.

Table 1. Ratio of ambient luminance to display luminance of the 25 experimental settings

		Ambient lighting												
	CCT (K)	Dark room	3,000							5,000				
	Illuminance (lx)		200	400	600	1,200	1,800	2,400	2,700	200	600	1,200	2,400	4,000
	Ambient luminance (cd/m²)		22.9	45.6	72.0	142.2	206.6	273.1	310.6	23.0	70.2	140.4	279.6	445.2
Display luminance (cd/m²)	150						1.38							
	200	0	0.11	0.23	0.36	0.71 (Repeat)	1.03	1.37		0.11		0.70	1.40	2.23 (Repeat)
	300				0.24				1.04					
	400	0	0.06	0.11		0.36		0.68				0.35	0.70	1.11 (Repeat)
	600				0.12	0.24					0.12			

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2.1. Experimental environment and ambient lighting

An LED lighting booth with dimensions of 100 cm (W) × 60 cm (D) × 60 cm (H) was used to control the ambient lighting conditions in a dark room. The interior of the lighting booth was painted in a neutral Munsell N7 color. A display was placed inside the LED lighting booth, and participants sat 1 m away from the display. As shown in Fig. 1, gray paper was used to cover the display such that the stimulus was presented to the participant with the field-of-view (FOV) of 11.9° × 6.7° (20.8 cm × 11.7 cm).

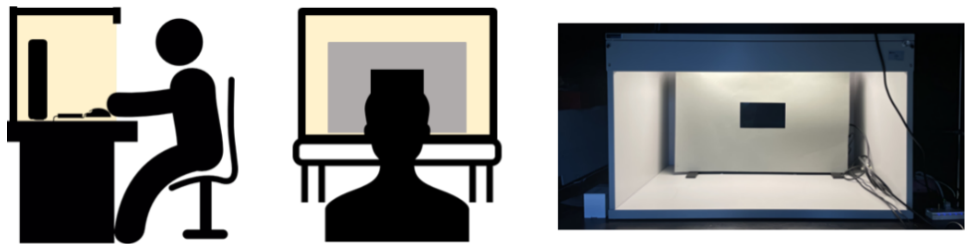

Fig. 1. Experimental environment.

Thirteen ambient lighting conditions, including dark conditions, were created using an LED lighting booth. These conditions comprised two ambient chromaticity levels in the CIE 1976 u′v′ color space: (0.2493 ± 0.0014, 0.5201 ± 0.0025) and (0.2058± 0.0012, 0.4852 ± 0.0009). The CCTs of two chromaticity levels were 3,041 ± 52 and 5,230 ± 33 K. For each ambient chromaticity, ambient illuminance was varied across seven levels (200, 400, 600, 1,200, 1,800, 2,400, and 2,700 lx) and five levels (200, 600, 1200, 2,400, and 4,000 lx), respectively. The intensity of light at the center of the booth floor, which was the brightest area in the experimental environment, was determined as the ambient chromaticity, luminance, and illuminance, as there was no reference white available under the experimental conditions. A spectroradiometer (Konica Minolta CS-2000) was positioned at the same location as the participant to measure the intensity of the light reflected by the surface. A THOULITE FS-VIS-IR spectrometer was placed at the center of the booth floor to measure the amount of ambient light falling on the surface.

2.2. Stimulus

The experiment used a 4 K OLED monitor with a maximum luminance of 727 cd/m^2 to present the stimuli. Single-color images were used as stimuli to eliminate the influence of image content on the display white points [3,4,26]. Stimuli with sixteen chromaticity were generated based on the pilot test result for each ambient lighting condition. During the pilot test, the participants adjusted the chromaticity of the stimulus and evaluated the range of chromaticity that appeared neutral under various lighting conditions. In the main experiment, the chromaticity of the stimuli was selected to encompass the range identified in the pilot tests.

In the 3,000 K ambient lighting condition, stimuli with CCTs of 4,800–6,500 K were used, while stimuli with CCTs ranging from 5,200 to 8,000 K were used in the 5,000 K ambient lighting condition. Stimuli with a CCT range of 6,000–8,000 K were used under dark room condition. Figure 2 shows the chromaticity of the stimuli measured in a dark room.

In this paper, all the measurement data are reported using CIE 1931 XYZ though the stimulus size is over 4° since the color measurement data is used not for color appearance description but for reporting the colorimetric values for displays.

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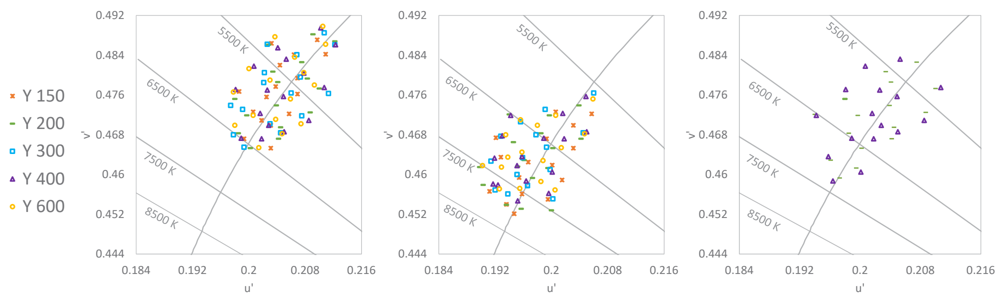

Fig. 2. Sixteen chromaticity levels of stimuli for each display luminance in the CIE u′v′ color space.

2.3. Psychophysical experimental procedure

The experiment constituted 25 experimental settings, and three settings among them were repeated to test the repeatability and reproducibility. The repeated conditions included the illuminance of 1,200 lx of 3,000 K CCTs with the display luminance of 200 cd/m^2 and the illuminance of 4,000 lx of 5,000 K CCTs with display luminance levels of 200 and 400 cd/m^2. The 28 experimental conditions were divided into five sessions to accommodate numerous experiments.

Prior to the experiment, the participants were provided with information about the experimental procedure and asked to sign an informed consent form. They adapted to the ambient light for two minutes while looking inside the booth during the experiment. After the adaptation period, a stimulus was presented for one second, followed by a black screen for four seconds. Note that the stimulus was presented only a short period of time to prevent the participant from adapting to the display luminance [24]. The participants were required to evaluate the color of the stimulus using a forced-choice method, i.e., whether it appeared yellow or blue and red or green by pressing the keypad. After evaluation, the next stimulus was presented. All stimuli were evaluated five times. For each ambient lighting condition, the display luminance levels varied from one to three, as summarized in Table 1. Stimuli with different display luminance levels were randomly presented under identical lighting conditions. For instance, under 1,200 lx of illuminance and 3,000 K of CCTs stimuli with luminance levels of 200, 400, and 600 cd/m^2 were presented in random order. The order of the ambient lighting conditions was also randomized.

2.4. Participants

Groups including 21, 20, 20, 19, and 18 participants took part in the five experimental sessions, respectively. As some participants participated in multiple sessions, 59 participants (36 males, 23 females) were included in the study. The participants were aged 19–43 years and had normal color vision, as verified using the Ishihara test. They were not professionals in the field of color science and were not informed of the purpose of the study.

3. Data analysis method

The participant responses regarding the hue of each stimulus, i.e., perceived as yellow or blue and red or green, were utilized to determine the hue of stimuli and display neutral points. The proportion of hue responses for each stimulus was obtained from all participants and represented as coordinates on the red–green and yellow–blue axes, as shown in Fig. 3. The dotted square in Fig. 3 represents the boundary of the responses generated with 0% and 100% responses.

The origin of the coordinates, which indicate the threshold of the two axes according to the psychometric function, was defined as the perceived neutral point [27]. The hue angle was converted to a 400-hue quadrature scale to express the hue as a percentage of two neighboring

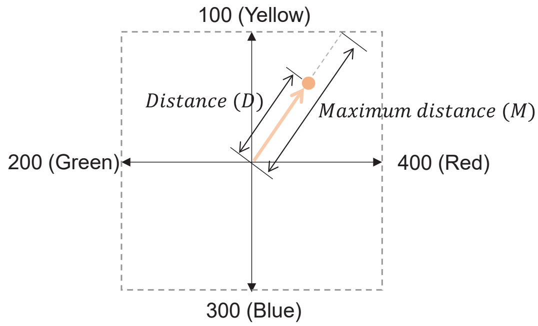

Fig. 3. Color coordinates of the hue evaluation results with the red–green and yellow–blue axes.

unique hues. Colorfulness was calculated as the normalized distance between the proportion of responses and the origin (D) by the maximum distance from the origin to the boundary i.e., dotted square passing the hue data point (M) using the following formula:

$$Colorfulness = \frac{Distance\ between\ proportion\ of\ responses\ and\ the\ origin\ (D)}{Maximum\ distance\ from\ the\ origin\ (M)} \tag{1}$$

Neutralness refers to how the stimulus appears neutral and is defined as follows:

$$Neutralness = 1 - Colofulness \tag{2}$$

For example, if a test color was evaluated as 75% red and 87.5% yellow, the coordinate in Fig. 3 is (0.25, 0.375). In that case, D and M are 0.451 and 0.601, resulting in Hue 62.6, Colorfulness 0.75 and Naturalness 0.25.

Neutralness was fitted to a bivariate Gaussian function in the CIE u′v′ diagram. The mean value of the fitted Gaussian function is used as the perceived neutral point. An example of the distribution of neutralness under 200 lx and 3,000 K CCTs of lighting with 200 cd/m^2 of display luminance 200 cd/m^2 is shown in Fig. 4.

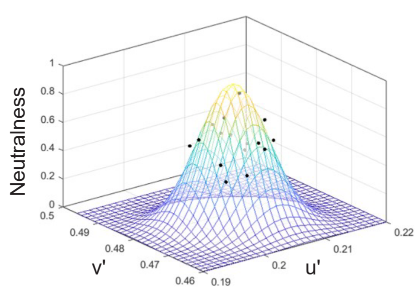

Fig. 4. Bivariate Gaussian function fitting on naturalness in the CIE 1976 u′v′ color space.

4. Experimental result

Following the data analysis method, Table 2 and Fig. 5 show the perceived display neutral points for all sessions, including the three repeated sessions. The ellipses around each display neutral point represent the range of chromaticity with neutralness scores greater than 0.95. The neutral range is broader along the yellow–blue axis than along the red–green axis, which is consistent with the findings of previous studies [14,28,29]. The CCTs of the display neutral points varied from 5,000 to 7,200 K depending on the display viewing conditions. In the next section, we discuss the influence of environmental factors on deviations in display neutral points, including ambient chromaticity, ambient luminance, display luminance, and surround ratio.

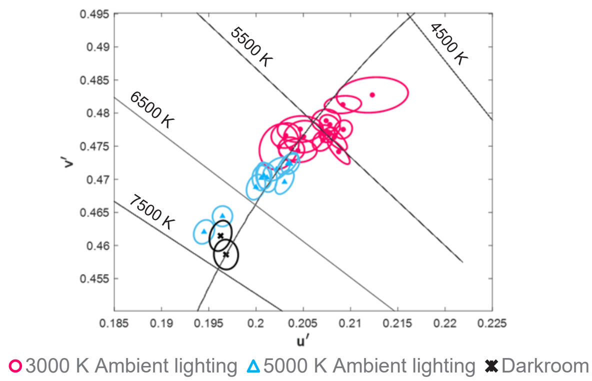

Fig. 5. Chromaticity of 28 display neutral points in CIE 1976 u′v′ color space.

4.1. *Intra-observer variations*

One of the five participant groups repeated the experiment under 4,000 lx and 5,000 K CCTs of lightings with 200 and 400 cd/m^2 luminance of the stimulus. Their repeatability was assessed by comparing the color difference of the display neutral points and the difference in the hue quadrature of the stimuli in the replicated experimental condition. The display neutral points between the two evaluations were 0.0015 and 0.0006 of Δu′v′ in CIE 1976 u′v′ color space as shown in Fig. 6 and the average of hue estimation differences between two trials were 13.7 ± 10.0 and 14.2 ± 11.2 as shown in Fig. 6(b) for each display luminance, respectively. The Δu′v′ differences in the neutral points collected in this study were comparable to those derived from other studies using a similar experimental method, ranging from approximately 0.0056 to 0.0196 [14,28]. These results indicate that the participants had reliable repeatability.

4.2. *Inter-observer variations*

In this study, different groups participated in five experimental sessions. Their reproducibility was evaluated based on the color difference of the display neutral point and the difference in the hue quadrature of stimuli in the duplicated experimental conditions, which were 1,200 lx and 3,000 K CCTs of ambient lighting with 200 cd/m^2 of display luminance. As shown in Fig. 7, the chromaticity difference of the display neutral points of the two groups was 0.0005 Δu′v′ in the CIE 1976 u′v′ chromaticity diagram, and the average of the hue quadrature differences of the stimuli was 27.3 ± 29.3. Two of the 16 stimuli, indicated by the filled dots in Fig. 7(b), exhibited large hue differences because their chromaticity was close to the chromaticity of the display neutral point. Otherwise, the average hue quadrature difference of stimuli was 18.8 ± 15.3. In the following analysis, the display neutral points for the three repeated experimental conditions were estimated by combining the repeated data, as the difference was not significant, as analyzed in Sections 4.1 and 4.2.

4.3. *Display neutral point in a darkroom*

Under dark room conditions, stimuli with display luminance of 200 and 400 cd/m^2 were evaluated. The CCTs of the display neutral point were 7,243 K and 7,069 K, respectively (0.197, 0.459, and 0.196, 0.461 in the u′v′ color space). The chromaticity difference between the neutral

Table 2. Chromaticity of perceived display neutral points

Ambient condition			Display luminance (cd/m^2)	Surround ratio	Display neutral point	
CCT (K)	Illuminance (lx)	Luminance (cd/m^2)			u'	v'
Darkroom	0	0	200	0	0.197	0.459
	0	0	400	0	0.196	0.461
	0	0	Average	0	0.197	0.460
3,000	200	22.9	400	0.06	0.204	0.474
	200	22.9	200	0.11	0.204	0.475
	400	45.6	400	0.11	0.203	0.477
	600	72.0	600	0.12	0.202	0.475
	400	45.6	200	0.23	0.207	0.476
	600	72.0	300	0.24	0.209	0.474
	1,200	142.2	600	0.24	0.205	0.478
	600	72.0	200	0.36	0.208	0.477
	1,200	142.2	400	0.36	0.207	0.479
	1,200	142.2	200	0.71	0.208	0.478
	2,400	273.1	400	0.68	0.205	0.476
	1,800	206.6	200	1.03	0.208	0.478
	2,700	310.6	300	1.04	0.208	0.476
	1,800	206.6	150	1.38	0.209	0.481
	2,400	273.1	200	1.37	0.212	0.483
5,000	200	23.0	200	0.11	0.195	0.462
	600	70.2	600	0.12	0.196	0.464
	1,200	141.1	200	0.71	0.203	0.470
	1,200	141.1	400	0.35	0.200	0.469
	2,400	279.6	200	1.40	0.204	0.472
	2,400	279.6	400	0.7	0.201	0.471
	4,000	445.2	200	2.23	0.203	0.472
	4,000	445.2	400	1.11	0.201	0.470

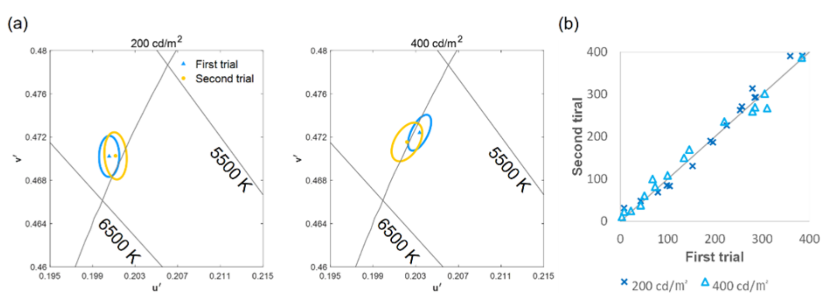

Fig. 6. (a) Chromaticity of display neutral points for 200 and 400 cd/m^2 display luminance levels. (b) Hue quadrature between intra-observers for the stimuli.

points of each display luminance was 0.0029 in $\Delta u'v'$ (Fig. 8). The CCTs of the display neutral points for the two levels of display luminance were approximately 7,200 K, which aligns with the findings of previous studies [15,28,30]. Choi and Suk, Cao and Luo, and Huang and Wei

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reported the dark-adapted white perception of self-luminous displays centered around 7,300, 7,600, and 7,900 K, respectively.

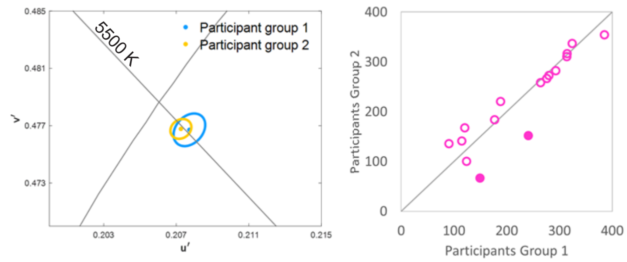

Fig. 7. (a) Chromaticity of display neutral points of two participant groups under the same experimental condition. (b) Hue quadrature comparison of stimuli between inter-observers.

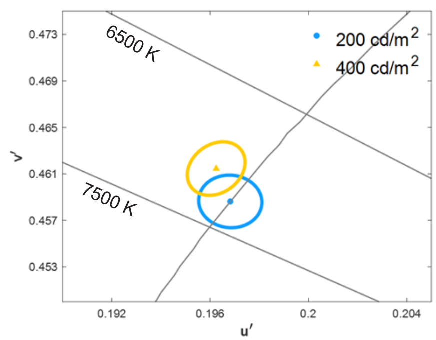

Fig. 8. Display neutral points of display luminance of 200 and 400 cd/m^2 in a darkroom.

4.4. Display neutral point change considering ambient chromaticity

Figure 9 shows the CCTs of the display neutral points according to ambient chromaticity. As the CCTs of the ambient chromaticity increased, the CCTs of the display neutral points also increased. This suggests that the ambient chromaticity dominantly influences the display neutral point. However, variations in color were observed under the same ambient chromaticity conditions. Under 3,000 K CCTs of ambient lighting, the CCTs of 15 display neutral points ranged from approximately 5,000 to 5,900 K. For ambient lighting with 5,000 K CCTs, the CCTs of eight display neutral points ranged from approximately 5,900 to 7,200 K.

The previous studies mentioned in the Introduction reported that CCTs of the display neutral points ranged from 3,500 to 6,000 K under ambient lighting with the CCTs of 3,000 K and from 5,200 to 7,100 K under ambient lighting with the CCTs of 5,000 K [14,15,24,28]. CCT ranges found in this study are well aligned with the previous studies but have a slightly narrower range.

4.5. Display neutral point change by the ambient and display luminance

In this section, we analyze the influence of the ambient luminance, display luminance, and surround ratio on the display neutral points. Figure 10 illustrates the changes in the CCTs of the display neutral points based on each parameter. As the ambient luminance increased, the CCTs of the display neutral points tended to be closer to the chromaticity of the ambient light. However, despite the constant ambient luminance, variations in the chromaticity of the display neutral points were observed. The variation reached up to 630 K of CCTs and 0.0096 in $\Delta u'v'$ in the CIE

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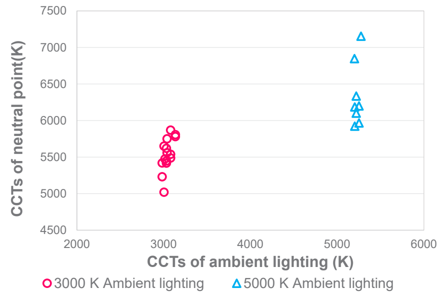

Fig. 9. CCTs of display neutral points according to the ambient chromaticity.

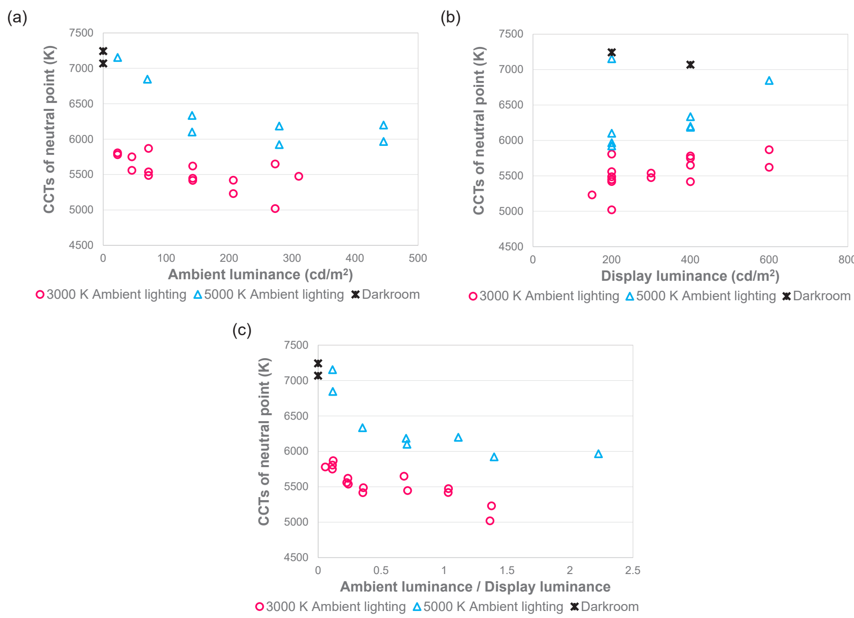

Fig. 10. (a) CCTs of display neutral points according to (a) ambient luminance, (b) display luminance, and (c) surround ratio.

1976 u′v′ color space. In addition, the display neutral point was not determined solely by the display luminance, as shown in Fig. 10(b). The chromaticity differences in display neutral points persisted even with constant display luminance, reaching up to 1,230 K of CCTs and 0.0137 in Δu′v′ in the CIE 1976 u′v′ color space. Figure 10(c) shows that the CCTs of the display neutral points change based on the surround ratio. The maximum color difference of display neutral points under the same surround ratio was measured as 0.0031 in Δu′v′ units. This implies that the variation in display neutral points under the same ambient chromaticity is primarily influenced by the ratio of ambient luminance to display luminance rather than their absolute intensity. As the surround ratio approaches zero, the display neutral point is expected to converge to the neutral point observed under darkroom condition. Notably, rapid changes in the display neutral point occurred within the range of surround ratios from 0 to 0.5. When the surround ratio exceeded 1.0, the display neutral point gradually converged to a specific level. The CCTs of the display neutral points converged to 5,000 and 5,900 K under 3,000 K and 5,000 K ambient lighting, respectively. The reason for the continued changes in the display neutral point beyond a surround ratio of

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1.0 is that the display can appear brighter than the ambient lighting until it is slightly above the surround ratio of 1.0, as the ambient lighting reflects off the display surface [14,18].

5. Perceived display neutral point prediction model and comparison with previous studies

Based on the experimental results, a perceived display neutral point prediction model was proposed, as shown in (3). This model predicted the CCTs of the display neutral point as it deviated further from the adapted white point with a decreasing surround ratio. The adapted white point indicates the perceived neutral point when the ambient luminance exceeds that of the display, which is similar to the condition for viewing hardcopy stimuli. This adapted white point should align with that estimated using the CAT model [7,8]. However, existing CAT models do not incorporate ambient chromaticity. Recognizing the need for improvements in the CAT model, this study utilized the experimental data of the converged neutral point at a higher surround ratio to determine the CCTs of the adapted white point. The surround ratio in the equation ranged from 0.05 to 2.7 based on our experimental conditions. To model the chromaticity of the neutral points based on the surround ratio and ambient chromaticity, we considered the point of convergence as an adapted white value when the surround ratio was higher than 1.0.

$$\begin{aligned} &\mathrm{CCT}_{Neutral\,point} = \mathrm{CCT}_{Adapted\ white} + 254.8(1 - \ln(S_R)) \\ &where\ 0.05 < S_R < 2.7,\ \mathrm{CCT}_{Adapted\ white} \leq 7,200\ K \end{aligned} \tag{3}$$

The performance of the display neutral point prediction model was tested using our new experimental data and the experimental results of previous studies [12,28,31]. We analyzed three studies because they provided detailed experimental conditions and results. Peng et al. [12] compared display neutral points under two levels of ambient luminance: 500 and 1,000 lx. They maintained the same display luminance level for both ambient luminance levels, resulting in a difference in the surround ratio. Their findings showed that as the ambient luminance increased, the CCTs of the display neutral point decreased from 5,670 to 5,207 K under 3,000 K ambient lighting and slightly changed from 6,084 to 6,008 K under 5,000 K ambient lighting. In another study by Choi and Suk [28], the ambient luminance remained at 500 lx, similar to that observed by Peng et al. However, the display luminance was approximately 1.5 times brighter, resulting in a lower surround ratio. The CCTs of the display neutral points in the work by Choi and Suk were 5,769 and 6,723 K under 3,000 and 5,000 K ambient lighting CCTs, respectively, which were higher than the values reported by Peng et al. Furthermore, Huang et al. [31] used 1,000 lx of ambient lighting, similar to the study by Peng et al., but with a display luminance that was more than twice as bright, resulting in a surround ratio decrease of more than two times. Consequently, the CCTs of the display neutral point were 5,975 and 7,082 K under 3,000 K and 5,000 K ambient lighting CCTs, respectively. These results imply that the display neutral point changes based on the surround ratio, even under similar ambient luminance and chromaticity conditions.

While the exact ambient luminance values were not specified in previous studies, we converted the illuminance of ambient lighting to ambient luminance, assuming that the observation angle was perpendicular to the surface and the surface reflectance was 1. Consequently, luminance was calculated by dividing illuminance by π, representing luminance for a perfect diffuser. Based on the gray-world assumption, we determined the ambient luminance using the following equation:

$$Ambient\ luminance = \frac{Illuminance}{\pi} \times \frac{1}{5} \tag{4}$$

Table 3 summarizes the experimental settings and results of the three previous studies and the predicted CCTs of the display neutral points using the proposed model. As shown in Fig. 11, the proposed model can predict changes in the display neutral point under varying display-viewing conditions for both our data and those of previous studies. The proposed model demonstrates a prediction error of 2.2% with our experimental data and a 4.5% error with data from previous studies.

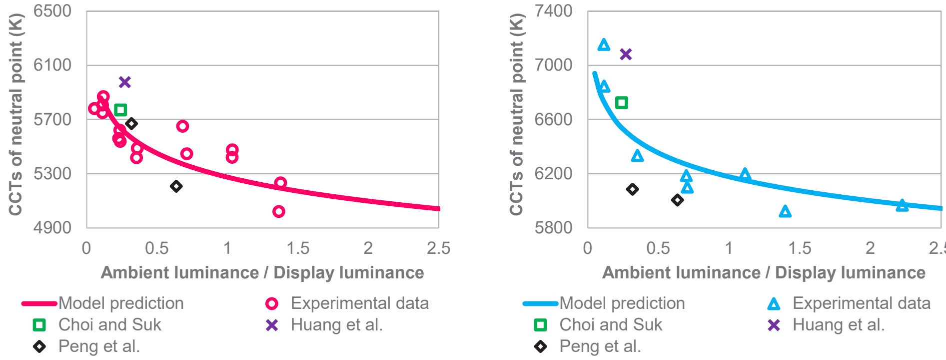

Fig. 11. CCTs of display neutral points according to the ratio of the luminance of ambient lighting to the display luminance. The left and right graphs represent the results under ambient lighting with 3,000 K and 5,000 K CCTs, respectively.

Table 3. Experimental settings and results of previous studies

Authors	Ambient CCTs (K)	Ambient illuminance (lx)	Converted ambient luminance (cd/m^2)	Display luminance (cd/m^2)	CCTs of a neutral point (K)	Predicted CCTs of a neutral point (K)
Peng et al.	3,000	500	32	100	5,670	5,566
		1,000	64	100	5,207	5,389
Huang et al.		1,000	64	235	5,975	5,607
Choi and Suk		600	38	158	5,769	5,636
Peng et al.	5,000	500	32	100	6,084	6,469
		1,000	64	100	6,005	6,293
Huang et al.		1,000	64	235	7,082	6,510
Choi and Suk		600	38	158	6,723	6,539

6. Conclusion

This study investigated the effects of ambient chromaticity, ambient luminance, and display luminance on perceived display neutral points considering 25 experimental settings. The chromaticity of ambient lighting significantly influences the neutral point of the display. Consistent with previous studies, our findings confirm that higher CCTs of ambient light correspond to higher CCTs of the display neutral point. The variation in the display neutral points under the same ambient chromaticity exhibit a stronger correlation with the ratio of ambient luminance to display luminance than with their absolute luminance values. At a high surround ratio, the display neutral point converged to a certain point. The CCTs of the adapted white point were 5,000 and 5,900 K under 3,000 K and 5,000 K CCTs of ambient lighting, respectively. As the surround ratio decreased, indicating that the ambient lighting became darker relative to the display luminance, the display neutral point shifted toward the neutral point under darkroom conditions. The difference in chromaticity between the display neutral point at a low surround ratio and the adapted display neutral point under two levels of ambient chromaticity levels was not significant. In both ambient chromaticity, the chromaticity difference between the neutral point at a low surround ratio and the adapted white point was approximately 0.01 $\Delta u'v'$ in the CIE 1976 $u'v'$ color space.

These findings highlight the importance of considering the relationship between environmental factors to enhance image quality on displays. Further research is required to incorporate wider ambient chromaticity and surround ratios below 0.05. Also, it is necessary to verify whether real room lighting or outdoor conditions will result in the same display neutral point as the lighting booth experiment.

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Data availability. The data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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