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Display neutral color prediction model based on ambient chromaticity and surround ratio

SEONYOUNG YOON,[1] YOUNGSHIN KWAK,[1,*] AND HYOSUN KIM[2]

[1] *Department of Biomedical Engineering, Ulsan National Institute of Science and Technology, Ulsan, Republic of Korea*
[2] *Samsung Display Co., Ltd., Youngin-City, Republic of Korea*
[*] *yskwak@unist.ac.kr*

Abstract: This study proposes a neutral color prediction model designed to determine the chromaticity of a display perceived as having no hue under various ambient lighting conditions. The model is based on neutral color data points collected across 68 experimental conditions, incorporating nine ambient chromaticity levels and multiple surround ratios. It predicts how the display's neutral color changes based on the luminance ratio between the display and ambient light, particularly when the display is brighter than the surrounding environment. Validation results demonstrate the model's effectiveness in predicting the preferred display white point.

1. Introduction

As displays become increasingly mobile, they are used in a wide variety of environments. The white point, which defines the chromaticity of white displayed on the screen, plays a vital role in an accurate color reproduction and consistent color representation. It serves as the reference for all other colors, and accurate white point settings allow users to experience a more natural and comfortable visual environment. Neutral color refers to the color perceived without any dominant hue by the human visual system under specific lighting conditions. To maintain the visual consistency of the display image across different environments, the display white point should be aligned with this neutral color [1–3].

When the display is brighter than the ambient lighting conditions, predicting the display's neutral color becomes challenging using traditional Chromatic Adaptation Transforms (CATs) embedded in color appearance models (CAMs). These models assume viewing conditions where the object is either as bright as or dimmer than a perfect diffuser, which can make the display appear more like a reflected color [4,5]. As the display emits light itself, it no longer aligns with the assumptions underlying traditional Chromatic Adaptation Transforms (CATs), leading to an inability to accurately predict the display's neutral color.

The authors' previous study has shown that when the surround ratio, i.e., the ratio of the ambient luminance to the display luminance is less than 1, the neutral color of the display changes according to the surround ratio [6]. It is not the absolute luminance of the display or ambient lighting that matters, but rather their relative luminance—the ratio of ambient luminance to display luminance [6–8]. In a dark room where the surround ratio is 0, observers perceive a display white of 7,200 K of correlated color temperature (CCT) as neutral (darkroom white), regardless of the display's luminance [9–12]. As the surround ratio increases from 0 to 1, the neutral color shifts from the darkroom white towards the chromaticity of the ambient lighting. This trend was consistently observed in experiments conducted under ambient lighting conditions of 3,000 K and 5,000 K of CCT, leading to the proposal of a model to predict this shift. However, the proposed model has limitations. First, it is based on CCT, which is non-uniform color unit. The chromaticity can vary even at the same CCT due to differences in Duv, which represents the distance to the black body locus on the CIE 1960 (u, v) coordinate. Second, the experiments were conducted under only two ambient chromaticity conditions, 3,000 K and 5,000 K of CCT,

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limiting the generalizability of the findings. To address these limitations, further research is needed, particularly involving experiments under a wider range of CCT and Duv conditions.

In this study, we aim to propose a neutral color prediction model that predicts the precise chromaticity of display neutral color under various ambient lighting conditions. It particularly highlights changes in the display neutral color when the display is brighter than the ambient light. The display neutral color under 42 conditions with seven levels of ambient chromaticity, five levels of surround ratio, and four levels of display luminance were investigated.

2. Experimental method

The experimental method follows the same experimental setting and procedure as detailed in the previous studies [6,13]. In those studies, the double forced-choice method demonstrated high reliability and consistency in collecting neutral color data. For specific experimental details, refer to the previous study. In the previous experiment, various levels of display luminance and ambient luminance were used to cover various levels of surround ratio across two ambient chromaticity conditions. Extending this research, this study investigated the neutral color under various levels of surround ratio across seven ambient chromaticity conditions.

2.1. Experimental environment and ambient lighting

The experiment utilized an LED lighting booth to control ambient lighting conditions. The booth measured 100 cm (W) × 60 cm (D) × 60 cm (H) and was painted a neutral Munsell N7 inside. Participants sat 1 m away from a display inside the booth, which was covered with gray paper to present stimuli within a field of view (FOV) of 11.9° × 6.7°.

Fourteen lighting conditions were organized, consisting of seven chromaticity levels (i.e., 4,500 K, 6,500 K, 8,500 K on the black body locus and 5,500 K with ±0.005 and ±0.01 Duv) and two ambient illuminance levels (600 and 1800 lux), determined based on the radiance measurements taken at the bottom of the viewing booth. Table 1 shows the details of the ambient conditions. The light intensity was measured as the reflected light on the white tile at the same position where the stimulus was presented during the experiment. Spectroradiometers were positioned at the participant's location for this measurement.

Table 1. Light intensity across fourteen ambient conditions

Ambient chromaticity	**4500 K**		**6500 K**		**8500 K**		**5500 K + 0.01 Duv**		**5500 K -0.01 Duv**		**5500 K + 0.005 Duv**		**5500 K -0.005 Duv**	
Illuminance (lx)	600	1800	600	1800	600	1800	600	1800	600	1800	600	1800	600	1800
CCT (K)	4785	4778	7292	7278	8743	8623	5911	5932	6246	6197	6035	6054	6077	6135
Duv	0.002	0.001	0.004	0.004	0.005	0.006	0.017	0.014	-0.010	-0.009	0.010	0.008	-0.004	-0.003
Y (cd/m^2)	85.5	254.4	86.9	258.5	96.6	291.0	87.9	261.9	86.8	261.8	88.6	257.5	85.8	256.3
u'	0.213	0.213	0.193	0.194	0.188	0.188	0.191	0.193	0.210	0.209	0.196	0.197	0.206	0.205
v'	0.490	0.489	0.462	0.462	0.451	0.452	0.488	0.486	0.459	0.460	0.480	0.478	0.467	0.467

2.2. Stimulus

The experiment utilized a 4 K organic light emitting diode (OLED) display (SONY BVM X-300) to present single-color images as stimulus. Stimuli with sixteen levels of chromaticity were generated based on the pilot test for each ambient lighting condition (Fig. 1). During the pilot test, five participants adjusted the chromaticity of the stimulus and evaluated the range of chromaticity that appeared neutral under various lighting conditions. Sixteen levels of chromaticity of the stimulus were selected to encompass the neutral range identified in the pilot tests. For each ambient chromaticity condition, four levels of display luminance were generated (i.e., 150, 200, 400, and 600 cd/m^2). This created five levels of surround ratio (i.e., 0.10, 0.31 (duplicated), 0.47, 0.93, and 1.24) for each ambient chromaticity, consisting of three levels within the range of 0 to 0.5 and one level each near 1.0 and above 1.0. This selection is based on a previous study [6], which showed that rapid changes in the display's neutral color occur within the surround ratio range of 0 to 0.5, whereas when the surround ratio exceeds 1.0, the display's neutral color gradually converges to a specific level.

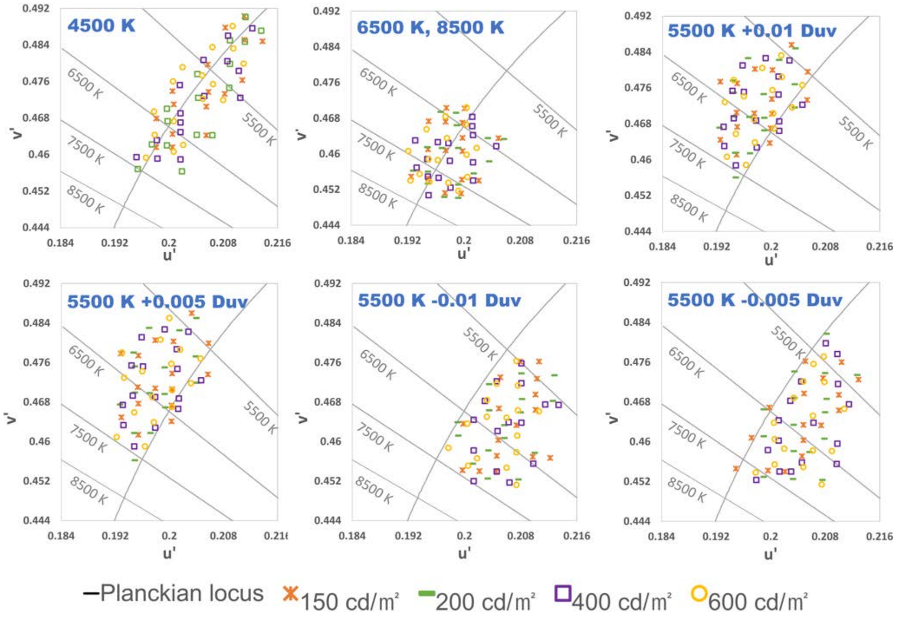

Fig. 1. Sixteen chromaticity levels of stimuli with four levels of luminance for each ambient condition in the CIE u′v′ color space.

2.3. *Psychophysical experimental procedure*

A total of eighteen participants, aged between 18 and 27 years and all with normal color vision, completed the experiment. None of the participants were professionals in color science, and they were unaware of the study's purpose.

The psychophysical experiment involved 42 conditions divided into seven sessions based on the ambient chromaticity. In each session, participants adapted to the ambient light for two minutes. Following the adaptation period, the stimulus was presented for one second, followed by a four-second display of a black screen. Participants then performed a double-forced-choice task to evaluate whether the stimulus appeared yellow or blue, and red or green. After the evaluation, the next stimulus was presented. Each stimulus was evaluated five times. Stimuli with different display luminance levels were randomly presented under identical lighting conditions, and the order of the ambient lighting conditions was also randomized.

3. Experimental result

The proportions of hue responses are plotted along the red–green and yellow–blue axes. The neutral color is assumed to correspond to the point where the proportions of hue responses reach 50% on both axes, indicating the origin. Colorfulness is calculated as the normalized distance from the hue proportion to the origin. Neutralness is defined as the complement of colorfulness, representing the absence of chromaticity. A bivariate Gaussian function is employed to model the distribution of neutralness for the chromaticity of the sixteen stimuli, and the chromaticity corresponding to the mean of the fitted function is estimated to be the neutral color. Further details on estimating the neutral color are outlined in the authors' previous study [6]. The neutral range is defined based on the thresholds in the psychometric function, at the points where colors begin to be perceived [14]. It is delineated by establishing thresholds of 25% and 75% for the proportions of hue responses, corresponding to 0.5 of neutralness.

Figure 2 shows the chromaticity of the neutral color across 68 conditions, including the author's previous study [6]. The starting point of the arrow represents the ambient chromaticity, while the ending point represents the display neutral color. It is notable that all arrows point to the display neutral color in the darkroom condition (darkroom white). Across various ambient chromaticity, the chromaticity of the neutral color ranges from 5,000 K to 7,500 K, with a deviation of ± 0.007 Duv. The neutral colors are clustered under the same ambient chromaticity. This indicates that ambient chromaticity predominantly influences the display neutral color. As the CCT and Duv of the ambient chromaticity increase, the CCT and Duv of the display neutral colors also increase.

The variations of neutral colors are observed under the same ambient chromaticity conditions. Under 3,000 K CCT of ambient lighting, the CCT of fifteen display neutral colors ranges from approximately 5,000 to 5,900 K. Under 4,500 K CCT of ambient lighting, the CCT of six display neutral colors ranges from approximately 5,500 to 6,000 K. For ambient lighting with 5,000 K CCT, the CCT of eight display neutral colors ranges from approximately 5,900 to 7,200 K. Under 5,500 K CCT of ambient lighting with four levels of Duv, the CCT of twenty-four display neutral colors ranges from approximately 6,100 to 6,500 K. For ambient lighting with 6,500 K and 8,500 K CCT, the CCT of twelve display neutral colors ranges from approximately 7,200 to 7,500 K.

The authors' previous study [6] showed that the variation in neutral colors under the same ambient chromaticity is primarily influenced by the ratio of ambient luminance to display luminance rather than their absolute intensity. Consistent with previous research findings, the chromaticity of the neutral colors remains consistent at the same surround ratio, which is calculated as the ratio of the white tile's luminance to the display luminance. When the surround ratio is zero, indicating darkroom conditions, the neutral color remains unaffected by ambient conditions and display luminance. As the surround ratio increases, the neutral colors tend to converge toward the chromaticity of the ambient illuminant. The trend of chromaticity changes in the neutral color is consistently observed under all ambient chromaticity conditions, except at 6,500 K and 8,500 K, where the neutral color remains identical to the darkroom white. When the

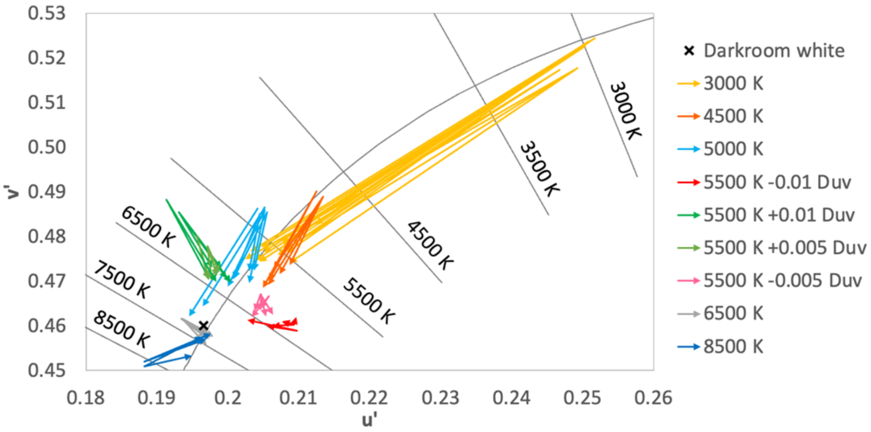

Fig. 2. Chromaticity of neutral colors for each ambient chromaticity in the CIE u′v′ color space.

surround ratio exceeds 1.0, the display neutral color gradually converges to a certain chromaticity. This occurs when the display luminance is equal to or lower than the diffuse white, similar to the surface color. Previous studies have shown that the neutral color varies depending on the viewing media [15,16]. They demonstrated that surface color achieves higher chromatic adaptation than self-luminous color due to texture and reflective properties. However, the experimental data reveals that the neutral color changes according to the surround ratio, converging when the surround ratio exceeds 1.0. It represents the neutral color of the display, appearing like the surface color when individuals adapt to the ambient illuminant. The converged chromaticity is defined as the ‘adapted white’, and it varies based on the ambient chromaticity (Table 2). The adapted white of the self-luminous color is similar to the independently illuminated surface colors in Li et al.’s study [16] when the ambient environments are similar. When there is no contextual information and no metamerism issues between the display and the lighting, the adapted white will be the same as the neutral color of the surface color.

Table 2. Average of chromaticity difference between predictions by CATs and adapted white

	Ambient Condition		Adapted White		Prediction Error (Δu’v’)						
	u’	v’	u’	v’	CAT16	Kwak et al.	Oh et al.	Zhai and Luo	Peng et al.	Zhu et al.	Ma et al.
3000 K	0.25	0.522	0.21	0.483	0.055	0.008	0.054	0.027	0.018	0.004	0.054
4500 K	0.213	0.49	0.209	0.475	0.016	0.005	0.015	0.01	0.01	0.004	0.016
5000 K	0.205	0.486	0.203	0.472	0.014	0.007	0.014	0.01	0.01	0.008	0.014
6500 K	0.194	0.462	0.197	0.459	0.004	0.015	0.005	0.009	0.008	0.015	0.004
8500 K	0.188	0.451	0.197	0.459	0.011	0.011	0.009	0.002	0.002	0.011	0.011
5500 K + 0.01 Duv	0.192	0.487	0.196	0.474	0.013	0.008	0.013	0.009	0.009	0.011	0.013
5500 K -0.01 Duv	0.21	0.46	0.208	0.461	0.002	0.011	0.002	0.005	0.005	0.01	0.002
5500 K + 0.005 Duv	0.196	0.479	0.199	0.472	0.007	0.007	0.007	0.006	0.006	0.009	0.007
5500 K -0.005 Duv	0.205	0.467	0.206	0.462	0.005	0.011	0.005	0.007	0.007	0.01	0.005
Average					0.014	0.009	0.014	0.009	0.008	0.009	0.014

4. Neutral color prediction model according to the ambient chromaticity and surround ratio

4.1. Concept of neutral color prediction model

A Neutral Color Prediction (NCP) model for displays is proposed to set an appropriate display white point under various ambient lighting conditions. When the luminance and chromaticity of the ambient illuminant are specified, the NCP model predicts the neutral color based on the surround ratio. The model is particularly effective at predicting changes in neutral color when the display is brighter than the ambient light. The predicted neutral color is located between darkroom white (approximately 7,200 K) and the adapted white. It reflects the neutral color changes according to the surround ratio when the display luminance is higher than the ambient condition. When the display luminance is lower than the ambient condition, the NCP model predicts the neutral color to be the adapted white, which is assumed as the experimental data of this study (Table 2). It is mathematically represented by the following equation:

$$\begin{bmatrix} L_N \\ M_N \\ S_N \end{bmatrix} = f(S_R) \times \begin{bmatrix} L_{AW} \\ M_{AW} \\ S_{AW} \end{bmatrix} + (1 - f(S_R)) \times \begin{bmatrix} L_{DW} \\ M_{DW} \\ S_{DW} \end{bmatrix} \tag{1}$$

The chromaticity of the neutral color is calculated based on the cone responses, as the chromatic adaptation relies on the sensitivity of the three cone responses. A 3×3 matrix in

CAM16, as recommended by the latest CIE guidelines, serves as the space sensor to convert between tristimulus values and cone responses. Cone responses of the display neutral color, denoted by $[LMS_N]$, are assumed to be between those of the darkroom white $[LMS_{DW}]$, and the adapted white $[LMS_{AW}]$. The ratio between two whites varies depending on the 'degree of neutral color shift $f(S_R)$', which is a function of surround ratio (S_R). When $f(S_R)$ is 0, it indicates that the neutral color's cone responses are identical to the darkroom white, while a value of 1 indicates that the cone responses match the adapted white. As the surround ratio increases, the degree of neutral color shift also increases and converges to 1 when the surround ratio is above 1.0, indicating convergence to the adapted white. The degree of neutral color shift is modeled as a power function of the surround ratio, with the simplest form representing a non-linear relationship. The exponent of the power function is set to 0.3 to ensure that the predicted neutral color falls within the neutral range. The formula is as follows:

$$f(S_R) = S_R^{0.3},\ (\textit{if}\ S_R{>}1.0, f(S_R) = 1.0) \tag{2}$$

4.2. Adapted white LMS_{AW}

Existing models for predicting neutral color do not account for the variation in display neutral colors when the surround ratio is lower than 1. Instead, they should accurately predict the adapted white for each ambient chromaticity. The performance of CAT in CAM16 and six other models developed by Kwak et al. [17], Oh et al. [18], Zhai and Luo [15], Peng et al. [19], Zhu et al. [20], and Ma et al. [21] is tested. To evaluate the performance of CATs, the reverse process of the CAM is employed. The test color for each ambient condition is investigated, which has J = 100, a = 0, and b = 0 in color appearance under reference condition. The reference condition is defined as Equi-Energy White (EEW) in all the models tested here. The performance of CATs is assessed by calculating the prediction errors in Δu'v' units between the predicted and experimental data (adapted white). A well-performing CAT will produce output values that match those of the adapted white.

As shown in Table 2, CAT16 shows low performance since it does not reflect the effect of ambient chromaticity on chromatic adaptation. The experiments are conducted in sufficiently bright conditions, resulting in the degree of adaptation in CAT16 approaching nearly 1.0. In the cases of Oh et al. and Ma et al., although they consider not only the ambient luminance but also the chromaticity of the ambient lighting, they still overestimate chromatic adaptation. Kwak et al., Zhai and Luo, Peng et al., and Zhu et al. demonstrate similar performance, with prediction errors ranging from 0.008 to 0.009 in Δu'v'. While Kwak et al. and Zhu et al. exhibit good performance for ambient conditions with low CCT, their performance decreases in high CCT ambient chromaticity, as their experiments are based solely on low CCT ambient conditions. Zhu et al.'s prediction of the adapted white is predominantly distributed near EEW for all ambient conditions. The predictions of Zhai and Luo, as well as those of Peng et al., are nearly identical, except for the 3,000 K CCT condition, as both groups proposed similar formats for the degree of adaptation functions. Although Peng et al. demonstrate the best performance overall, prediction errors are observed to be up to 0.0018 in Δu'v' in the 3,000 K CCT condition.

Most models predict that the neutral color lies between the ambient chromaticity and the EEW. However, experimental results show that it does not fall within this range, indicating a need for improvements in the structure of CATs. Due to the limitations of existing models in predicting the adapted white, this study relies solely on experimental data to determine the adapted white.

4.3. Neutral color prediction model

The NCP model is proposed to predict the tristimulus value of the display neutral color based on the ambient chromaticity and surround ratio. The average chromaticity difference between experimental data and predicted neutral color is 0.0026 ± 0.0018 in 1976 u'v' color space.

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Input data: chromaticity of Darkroom white in CIE 1976 $u'v'$ chromaticity coordinates, CCT and luminance of ambient condition (CCT and luminance of the white tile positioned in the stimulus under ambient lighting), and display luminance

- Darkroom white: $u'_{DW} = 0.197$, $v'_{DW} = 0.459$
- CCT of ambient condition (K): $CCT_{Ambient}$
- Luminance of ambient condition (cd/m^2): Y_A
- Display luminance (cd/m^2): Y_D

Output data: chromaticity of neutral color in CIE 1976 $u'v'$ chromaticity coordinates

- Chromaticity of neutral color: u'_N, v'_N

Step 1: Utilize a table below to compute the chromaticity of adapted white (u'_{AW}, v'_{AW}) based on the CCT and Duv of the ambient lighting. For ambient conditions near the Planckian locus, linear interpolation is employed. Set values for CCT_a and CCT_b in the table, where $CCT_a < CCT_{Ambient} < CCT_b$, and u'_a, v'_a and u'_b, v'_b represent the adapted white for CCT_a and CCT_b, respectively.

Ambient condition		**3000 K**	**4500 K**	**5000 K**	**6500 K**	**8500 K**	**5500 K + 0.01**	**5500 K -0.01**	**5500 K + 0.005**	**5500 K -0.005**
Adapted white	u'_{AW}	0.21	0.209	0.203	0.197	0.197	0.196	0.208	0.199	0.206
	v'_{AW}	0.483	0.475	0.472	0.459	0.459	0.474	0.461	0.472	0.462

$$\gamma = \frac{CCT_{Ambient} - CCT_a}{CCT_b - CCT_a}, when\ CCT_a < CCT_{Ambient} < CCT_b \tag{3}$$

$$u'_A = u'_a \times (1-\gamma) + u'_b \times \gamma \tag{4}$$

$$v'_A = v'_a \times (1-\gamma) + v'_b \times \gamma \tag{5}$$

Step 2: Convert chromaticity of adapted white (u'_{AW}, v'_{AW}) and darkroom white (u'_{DW}, v'_{DW}) to tristimulus values $(X_{AW}, Y_{AW}, Z_{AW}, X_{DW}, Y_{DW}, Z_{DW})$ based on Y_D.

$$Y = Y_D, \tag{6}$$

$$X = Y \cdot \frac{9u'}{4v'}, \tag{7}$$

$$Z = Y \cdot \frac{12 - 3u' - 20v'}{4v'} \tag{8}$$

Step 3: Convert tristimulus values of adapted white (X_{AW}, Y_{AW}, Z_{AW}) and darkroom white (X_{DW}, Y_{DW}, Z_{DW}) to cone responses $(L_{AW}, M_{AW}, S_{AW}, L_{DW}, M_{DW}, S_{DW})$ using the matrix provided in CAT16 (M_{CAT16}).

$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = M_{CAT16} \begin{bmatrix} X \\ Y \\ X \end{bmatrix} = \begin{bmatrix} 0.401288 & 0.650173 & -0.051461 \\ -0.250268 & 1.204414 & 0.045854 \\ -0.002079 & 0.048952 & 0.953127 \end{bmatrix} \begin{bmatrix} X \\ Y \\ X \end{bmatrix} \tag{9}$$

Step 4: Calculate impact of ambient chromaticity ($f(S_R)$) based on surround ratio.

$$f(S_R) = \left(\frac{Y_A}{Y_D}\right)^{0.3} \left(if\ \frac{Y_A}{Y_D} > 1.0,\ f(S_R) = 1.0\right) \tag{10}$$

Step 5: Calculate cone responses of neutral color (L_N, M_N, S_N).

$$\begin{bmatrix} L_N \\ M_N \\ S_N \end{bmatrix} = f(S_R) \times \begin{bmatrix} L_{AW} \\ M_{AW} \\ S_{AW} \end{bmatrix} + (1 - f(S_R)) \times \begin{bmatrix} L_{DW} \\ M_{DW} \\ S_{DW} \end{bmatrix} \tag{11}$$

Step 6: Convert cone responses of display neutral color (L_N, M_N, S_N) to tristimulus values (X_N, Y_N, Z_N) using inverse matrix (M_{CAT16}^{-1}).

Step 7: Convert tristimulus values of display neutral color (X_N, Y_N, Z_N) to chromaticity in CIE 1976 $u'v'$ chromaticity coordinates (u'_N, v'_N).

Note that the proposed model is applicable within the tested experimental environment. It is effective for surround ratios of 0.1 or higher and has been validated for displays with a field of view of approximately 10 degrees, corresponding to typical mobile display sizes. Additionally, the model is suitable for ambient lighting conditions with a CCT range of 3000 K to 8500 K and a Duv range of ±0.01.

5. Verification of the neutral color prediction model

The neutral color prediction model is developed based on the assumption that people prefer the chromaticity perceived as neutral to serve as the white point [22]. Validation of the model is performed to assess whether the predicted neutral color aligns with individuals' preferences and whether it can accurately predict the preferred display white point for images with various contents.

5.1. Experimental method

The experimental environment and instruments were consistent with those used in the main experiment. To investigate the preferred white point based on ambient lighting, extreme conditions of 1,200 lx with a CCT of 3,000 K were implemented, as these are expected to most effectively demonstrate the model's performance. On the display, two images were presented on the left and right sides, each measuring 720 × 480 pixels. To simulate stimuli while maintaining peak luminance, the activated screen area was adjusted to remain below 50% of the total screen area. The display was covered with mid-gray paper featuring two square holes of smartphone dimensions (7.8 × 11.7 cm). Both square holes were of equal size, with a distance of 4.5 cm between them. When participants were seated 80 cm away from the display inside the booth, the field of view through each hole measured 5.6 × 8.4°.

As stimuli, four contents were used: laundry, artifactual image (e-mail), food, and a cat, representing a real-world scene and a typical application screen on the display (Fig. 3(b)). The stimulus was rendered with seven levels of display white point, with CCT ranging from 4,300 K to

6,600 K in approximately 400 K intervals along the Planckian locus. The stimulus was generated by characterizing the display using the Gain-Offset-Gamma (GOG) model proposed by Berns [23]. When the white point in the images is converted to the target tristimulus values (target CCT's XYZ tristimulus values), the digital RGB values of the images are rendered proportionally to the change in white. As all content contains white, the chromaticity white point of each stimulus is used to represent the stimulus's chromaticity. Figure 3(a) shows the chromaticity of the stimulus for each luminance level. There were two levels of surround ratio based on the display luminance levels: 150 and 600 cd/m^2.

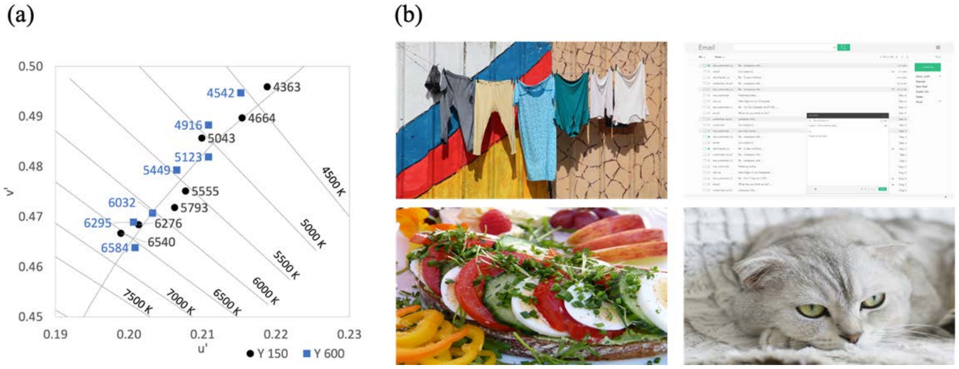

Fig. 3. (a) Chromaticity of stimuli for each ambient chromaticity in the CIE u'v' color space. (b) Four contents: laundry, artifactual image (e-mail), food, and cat.

The method of paired comparison was used in the psychophysical experiment. Participants adapted to the ambient condition for two minutes. Subsequently, two stimuli were presented for two seconds, followed by a black screen for four seconds. Without viewing the original image, participants selected the preferred image based on the overall impression of image quality. For each luminance level and content of the stimulus, a total of 49 pairs were evaluated, covering all combinations of the seven stimuli. This included comparing identical images and repeating mirrored positions to mitigate any left-to-right bias. A total of 588 evaluations were conducted for six images and two levels of display luminance. Seventeen participants took part in the experiment, consisting of eight males and nine females, with an average age of 22.4 ± 3.0 years. All participants had normal color vision, which was confirmed through the Ishihara test. None of the participants were informed of the study's purpose.

5.2. Experimental result

Comparative proportion data is used to analyze the psychological scale, utilizing the z-score [24]. By comparing identical stimuli, observer performance is assessed. When averaging the responses of all participants for the 84 pairs of identical stimuli, the probability of choosing the stimulus on the left side is 52.8%. This suggests that the observers perform well and that there is no discernible bias based on the position of the stimulus in the experiment.

Table 3 and Fig. 3 present the CCT and chromaticity of the most preferred white points and predicted neutral color by the NCP model. As the surround ratio increases, the influence of ambient lighting on the preferred display white point becomes more pronounced. On average, the CCT of the preferred white point is 5,952 K and 5,615 K for surround ratios of 0.28 and 1.12, respectively. The average chromaticity difference between the preferred white point and the predicted neutral color is 0.008 and 0.004 in the 1976 u'v' color space.

The experimental results demonstrate that changes in the CCT of the preferred white point in images due to the surround ratio are similar to those of neutral colors. A lower surround

Table 3. CCTs of preferred white point and predicted neutral color

	CCTs of preferred white point (K)						
	Cat	**Food**	**Laundry**	**E-mail**	**Average**	**Model Prediction**	**Prediction Error ($\Delta u'v'$)**
High Sr (1.12)	5555	5555	5793	5555	5615	5118	0.008
Low Sr (0.28)	6295	5449	6032	6032	5952	5669	0.004

ratio results in a higher CCT. However, slight differences were observed in the selected CCTs. Overall, observers preferred a higher CCT in images than the neutral color. Additionally, content dependency was evident. For ‘Food’ image, there was no CCT change with varying surround ratios. Under low surround ratio conditions, a lower CCT was preferred than others, likely due to the inherent association of food-related stimuli with warm and natural tones.

6. Conclusion

This study investigates how neutral color varies with different levels of surround ratio across seven ambient chromaticity conditions. The chromaticity of neutral colors clusters closely according to the ambient chromaticity. Variations in neutral colors under the same ambient chromaticity depend on the surround ratio, which is the ratio of ambient luminance to display luminance. As the surround ratio increases, the neutral color shifts from darkroom white to adapted white. This trend is consistently observed across all ambient chromaticity conditions.

Based on the 68 neutral color data, a Neutral Color Prediction (NCP) model is proposed to predict the display neutral color under various ambient lighting conditions. The NCP model accounts for changes in neutral color based on the surround ratio, specifically in situations where the display is brighter than the surrounding condition. Additionally, the predicted neutral color is similar to the preferred white point tested using four content images, although a slightly higher CCT was preferred for the images, and content dependence was observed.

It should be noted that our study was conducted under limited conditions. Given the importance of the research topic—determining the proper white point for displays—further research is required to gather data on display neutral colors under a wider range of ambient chromaticity conditions, using various stimulus types and more advanced experimental methods. In particular, as this experiment was conducted in a viewing booth, experiments under real-world conditions with high-luminance displays are necessary.

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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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