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Assessment of white for displays under dark- and chromatic-adapted conditions

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Abstract: This study aims to investigate the white perception of mobile display devices under dark-adapted and chromatic-adapted conditions. The white perception was modeled with error ellipses and bivariate Gaussian distributions. The dark-adapted white encompassed a rather large area centered around 7300 K, slightly above the Planckian locus. The chromatic-adapted whites were highly dependent on the ambient illuminant, and were not parallel to the Planckian locus. Combined, the white region encompassing 6179 to 7479 K in correlated color temperature and −0.0038 to 0.0144 in Duv was suggested. The results of this study are expected to be the basis for enhanced white appearance on mobile display devices.

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OCIS codes: (330.1690) Color; (330.1720) Color vision; (330.5510) Psychophysics; (330.7320) Vision adaptation.

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1. Introduction

Over the past several years, much attention has been paid to enhancing the color appearance of mobile devices. It has been acknowledged that white, which is defined as a color sensation that is devoid of any hue, has a fundamental role in display color appearance [1]. However, despite the exact specification of the meaning of white, there is still considerable ambiguity regarding its chromaticity. The standards for white points differ substantially depending on the industry and country. For example, a recommended white point for graphic arts is D50, while for photography it is D65 [2]. With regard to country, the U.S. broadcasting standard uses D65 as the white point, whereas D93 is the broadcast standard in Japan [3]. Moreover, there is quite a bit of disagreement among various psychophysical experiments in the literature.

Correlated color temperature (CCT) has been a convenient and widely used specification of the white point of display devices and the color of light sources. In one of the earliest psychophysical experiments on white perception, Priest [4] observed the average white chromaticity of four subjects at 5200 K under dark-adapted conditions. Helson and Michels [5], on the other hand, reported the dark-adapted white chromaticity at 15000 K based on data from three subjects. In response to these findings, Hurvich and Jameson [6] provided white threshold contours in color temperature, instead of a single chromaticity point. Similarly, Honjyo and Nonaka [7] provided a rather large region of white perception, ranging from approximately 5500 to 10000 K.

Interestingly, these studies had an implicit assumption that chromaticity coordinates on the Planckian locus would appear white. However, the stimuli of precisely the same CCT could have very different chromaticities and therefore appear quite differently. Such shifts away from the Planckian locus are expressed by Duv, which is defined as the closest distance from the Planckian locus on the CIE 1960 *uv* chromaticity [8]. It has been often questioned whether the chromaticity coordinates on the Planckian locus would really be perceived as white. Recently, Ohno and Fein [9] indicated that light sources below the Planckian locus are preferred. In a similar experiment, a line of whites was observed that lies above the Planckian locus at CCTs higher than 4000 K and below the Planckian locus for lower CCTs [10]. Most recently, Chauhan *et al.* [11] reported average achromatic settings with positive Duv values, while Smet *et al.* [12] reported negative Duv values. In response to these findings, it has become accepted that CCT and Duv should be considered together to enhance white perception [13].

Although white perception has been studied intensively, differing values have been reported, indicating that white perception depends largely upon the specifics of the viewing

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conditions, such as the viewing modes, ambient illuminants, and subjects. Most of the above studies investigated white perception in the aperture or illumination mode. Equally important, but less well understood, is the illuminant mode, in which the color is perceived as belonging to the self-luminous source of light [14]. Moreover, a majority of studies have investigated white perception only under dark-adapted conditions. However, mobile devices are generally observed in various illuminants, in which the color perception may differ considerably from dark surroundings due to chromatic adaptation. Lastly, the sample sizes of the previous studies seem to have been insufficient, which is a particular problem in psychophysics, in which the sample size is usually small but the individual differences are large [15]. As such, this paper builds on and extends previous studies by observing the white perception of a self-luminous display presented in a real rather than a simulated environment, lit by illuminants with various chromaticities. By doing so, this study aims to derive an empirical model to predict the degree of whiteness as a function of position in color space via a series of dark-adapted and chromatic-adapted psychophysical experiments.

2. Dark-adapted white

In the first part of the study, the white perception of a self-luminous display was investigated under dark-adapted viewing conditions. For a psychophysical experiment, the degrees of whiteness of 97 chromaticity points were evaluated in a dark room. The data set was then fitted into an error ellipse and a bivariate Gaussian distribution.

2.1 Stimuli

A reading article composed of black texts on a white background was displayed on a tablet computer with a 9.7-inch LED-backlit IPS LCD display, as one of the most typical mobile device viewing conditions, with white color dominantly displayed on the screen, as shown in Fig. 1(a). The viewing distance was approximately 30 cm (the distance of distinct vision), providing a stimulus field of view (FOV) of 43.8°. Hence, all of the chromaticity values were calculated with the CIE 10° observer. When measured with a spectroradiometer (Konica Minolta CS-2000), the native white point of the tablet computer was (0.1957, 0.4621) in the CIE 1976 *u' v'* chromaticity, which is equivalent to a CCT of 7072 K. The coordinates and luminance of the *R* (Red), *G* (Green), and *B* (Blue) primaries at peak output were as follows: *R* = (0.4473, 0.5229, 54.96 cd/m^2), *G* = (0.1454, 0.5639, 204.53 cd/m^2), and *B* = (0.1690, 0.1733, 16.34 cd/m^2). The tablet computer was switched on for at least an hour prior to starting the visual experiments to ensure a stable luminance output.

A total of 97 sets of white backgrounds were set up as experimental chromaticity points. The 96 chromaticity points consisted of a full range of CCTs from 2500 to 20000 K, at seven different Duv levels (–0.015, –0.010, –0.005, 0, 0.005, 0.010, and 0.015), as shown in Fig. 1(b). The stimuli were located at 15 isotemperature lines of, nominally, 2500, 3000, 3500, 4000, 4500, 5000, 6000, 7000, 8000, 9000, 10000, 11000, 12000, 15000, and 20000 K. The intervals between each isotemperature line were carefully adjusted according to the micro-reciprocal degree [16]. The native white point was added to create a total of 97 chromaticity points. The colorimetric values were measured using a spectroradiometer and were averaged for each of the 15 CCT groups, as listed in Table 1. The variations in CCT at different Duv levels were within ± 15 K from the average at 2500 K and ± 800 K from the average at 20000 K, and the luminance was kept within ± 20 cd/m^2 from an average value at each CCT group.

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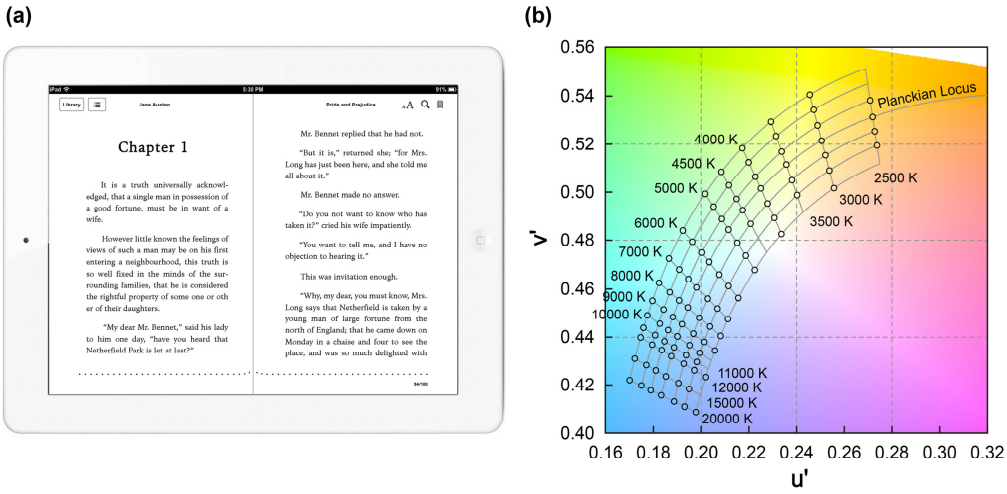

Fig. 1. (a) A reading article composed of black texts on a white background; (b) a total of 96 chromaticity points at 15 different CCTs and at seven different Duv levels in the CIE 1976 *u'* *v'* chromaticity.

Table 1. The average CCT (K), luminance (cd/m^2), and *x*, *y*, *u'*, and *v'* values at each CCT group

CCT group	CCT (K)	Luminance (cd/m^2)	*x*	*y*	*u'*	*v'*
2500 K	2544	86.43	0.4671	0.4031	0.2707	0.5253
3000 K	3068	102.00	0.4334	0.4047	0.2482	0.5204
3500 K	3526	114.52	0.4072	0.3990	0.2337	0.5145
4000 K	4042	127.05	0.3794	0.3776	0.2243	0.5012
4500 K	4560	142.42	0.3609	0.3748	0.2131	0.4977
5000 K	5060	146.22	0.3435	0.3515	0.2106	0.4840
6000 K	6079	158.59	0.3208	0.3308	0.2030	0.4701
7000 K	7018	158.49	0.3061	0.3165	0.1982	0.4602
8000 K	8010	156.98	0.2950	0.3054	0.1945	0.4522
9000 K	8974	150.08	0.2871	0.2962	0.1922	0.4456
10000 K	10006	143.75	0.2791	0.2918	0.1880	0.4417
11000 K	11092	134.07	0.2739	0.2852	0.1867	0.4368
12000 K	12219	126.47	0.2716	0.2766	0.1883	0.4308
15000 K	15170	117.63	0.2623	0.2685	0.1843	0.4241
20000 K	19317	108.66	0.2572	0.2590	0.1840	0.4167

2.2 Procedure

A total of 56 college students (28 males and 28 females) were recruited for the experiment, with an average age of 22.61 years and a standard deviation of 3.06 years. All of the participants were paid volunteers. They had normal or corrected-to-normal visual acuity, with no significant color deficiencies. Ethical approval was obtained prior to the commencement of all of the studies concerning human participants (Approval number: KH2016-6). The study adopted rating experiments, in which the participants were asked to rate the whiteness levels of each presented stimulus using a five-point Likert scale ranging from 1 (least white) to 5 (most white). Rating experiments are suggested to be more accurate compared to setting experiments, in which participants are asked to adjust the chromaticity of each stimulus until it appears white [17].

The subjects spent one minute in a dark room before starting the evaluation to adapt to the dark environment, and the measured illuminance at the subject's position was less than 1 lux.

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The 97 stimuli were presented in a random order to eliminate any sequential effect on the subjects' evaluation. The viewing time for each stimulus was not fixed, as viewing time is known to has very little, if any, effect on the perception of white [10]. To reduce the bias in color perception inflicted by the surrounding environment, the experiment was conducted with achromatic, grayish survey sheets on an achromatic, grayish desk, and the participants were instructed to put on achromatic, grayish gloves, as shown in Fig. 2. The experiment lasted approximately ten minutes. The room's ambient conditions were maintained for human comfort [18]: ambient temperature = 24.2 ± 2 °C; ambient humidity = 37 ± 5%; and ambient noise = 45.2 ± 10 dB(A).

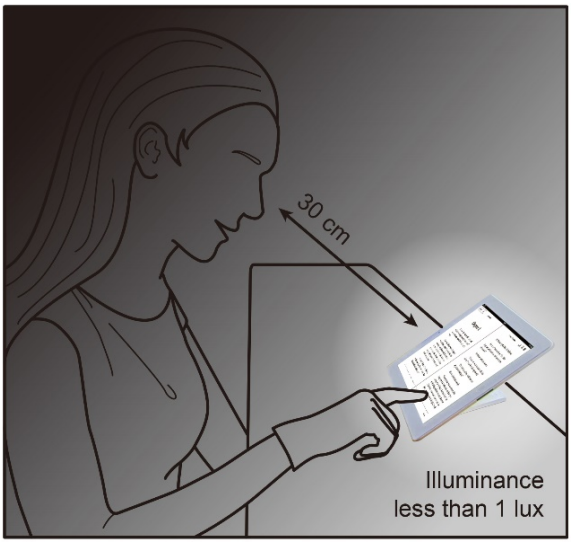

Fig. 2. Experimental environment with a viewing distance of approximately 30 cm. The measured illuminance at the subject's position was less than 1 lux when the tablet computer was turned off. The participants were instructed to put on achromatic, grayish gloves.

2.3 Results and discussion

The error ellipse has been frequently adopted to represent the yes and no boundary for the perception of white. The bivariate Gaussian distribution is a logical extension to the error ellipse that incorporates a full data set [19]. The adoption of a bivariate Gaussian distribution offers several advantages compared to fitting an error ellipse, for which only "yes" ratings are taken into account. Since all data points are used, fitting a distribution is less susceptible to outliers and hence more accurate in predicting the center. Moreover, it becomes much less critical to have a grid with high-rated values fully enclosed by low-rated values. The bivariate Gaussian distribution also results in a simple metric to predict the degree of whiteness. However, the size of the white region is not directly comparable to those in previous studies, which have generally adopted error ellipses for analysis. Hence, the results were first analyzed by fitting an error ellipse to the stimuli that scored five points. In the second phase, the full data set of 97 ratings was analyzed to develop a bivariate Gaussian model that could predict the degree of whiteness.

In the first phase of the analysis, only the chromaticity points that scored five points were extracted out of the 97 chromaticity points for each participant. These chromaticity points were then fitted into a one-standard-deviation ellipse. The size of the major and minor axis, the center, the angle of rotation, and the area of the ellipse are given in Table 2.

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Table 2. The size of the major and minor axis, the center, the angle of rotation, and the area of ellipse

Major axis	Minor axis	u'_{center}	v'_{center}	CCT $_{center}$ (K)	Duv $_{center}$	Angle (°)	Area (10^{-4})
0.0254	0.0090	0.1963	0.4590	7246	0.0010	60	7.20

Secondly, the full data set was analyzed by taking into account the ratings of all 97 presented stimuli. The 5432 ratings (56 subjects × 97 chromaticity points) were modeled with a bivariate Gaussian distribution, as described by Eq. (1):

$$S_{whiteness} = a_6 \cdot e^{-0.5[a_1(u'-a_3)^2+a_2(v'-a_4)^2+2a_5(u'-a_3)(v'-a_4)]}, \quad (1)$$

with $S_{whiteness}$ as the degree of whiteness, a_1 to a_6 as the fitting parameters, and u' and v' as the CIE 1976 chromaticity coordinates. The resulting distribution and the mean ratings for each chromaticity point are plotted in Fig. 3. The 25%, 50%, 75%, and 95% elliptical contours of the bivariate Gaussian model were also plotted. The goodness of fit was quantified by calculating the Spearman correlation coefficient ρ and standardized residual sum of squares (*STRESS*). The correlation coefficient was 0.85 ($p < 0.01$), and the *STRESS* value was 0.11, resulting in a simple but quite accurate metric to predict the degree of whiteness viewed by a dark-adapted average observer, as a function of position in the CIE 1976 u' v' chromaticity. The fitting parameters and the center of the bivariate Gaussian model are summarized in Table 3.

Table 3. Fitting parameters $a_{1\text{-}6}$ of the bivariate Gaussian distribution, and the u', v', CCT, and Duv of the center

a_1	a_2	a_3	a_4	a_5	a_6	u'_{center}	v'_{center}	CCT $_{center}$ (K)	Duv $_{center}$
3093.57	850.50	0.19	0.46	−702.05	2.75	0.1947	0.4599	7300	0.0026

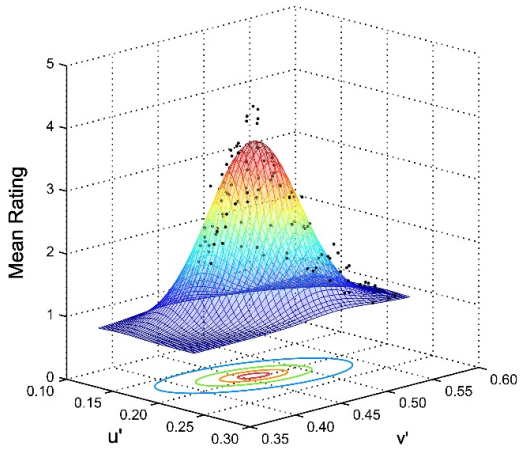

Fig. 3. Bivariate Gaussian distribution and its elliptical contours, as obtained by fitting the full data set in the CIE 1976 u' v' chromaticity. The mean ratings for each chromaticity point are also shown as dots to visualize the goodness of fit.

The one-standard-deviation error ellipse and the 50% bivariate Gaussian ellipse were plotted together in the CIE 1976 u' v' chromaticity, as shown in Fig. 4. The dark-adapted white encompassed an area, rather than a point or a line as reported by previous studies [10, 20], which is consistent with the findings from Smet *et al.* [12]. The one-standard-deviation error ellipse, plotted as a dashed line, encompassed 5236 to 11122 K in CCT and −0.0075 to 0.0099 in Duv. The 50% bivariate Gaussian ellipse, plotted as a solid line, encompassed 5284 to 11337 K in CCT and −0.0081 to 0.0134 in Duv. When fitted with 50% bivariate Gaussian ellipse, the size of the ellipse was close to the error ellipse in the CCT direction. However, the

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bivariate Gaussian ellipse was slightly larger in the Duv direction, indicating that the error ellipse is limited by the range of the grid points in the Duv direction. Hence, 50% bivariate Gaussian ellipse was adopted as the white region for further analysis. The direction of the major axis was aligned with the Planckian locus, which is in good agreement with the results obtained by Chauhan *et al.* [11]. The range of white perception was smaller in the red–green Duv direction than in the yellow–blue CCT direction. As seen in Fig. 4, the results of the experiment were plotted over the ANSI C78.377 [8] and CIE S 004 [21] white regions for light sources. It can be seen that the low and high CCT ends of the current standards tend to respectively overestimate and underestimate the dark-adapted white region. The data presented here suggest that self-luminous displays that meet the current standards would probably not appear white under the viewing conditions employed in this study, which was also supported for the illumination mode [12] and object mode [17].

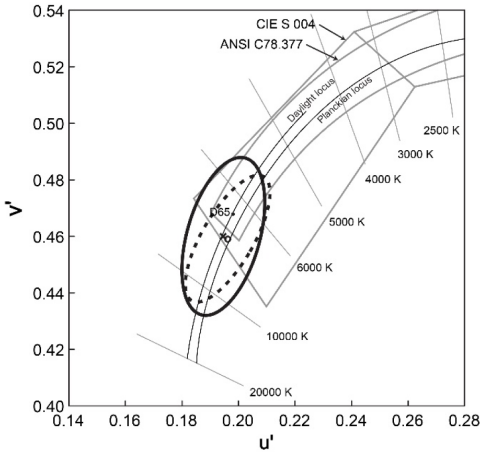

Fig. 4. The one-standard-deviation error ellipse and the 50% bivariate Gaussian ellipse are plotted as dashed and solid lines, respectively. The centers of the two respective ellipses are marked with a circle and a cross. The ANSI C78.377 and CIE S 004 are also shown, along with the Planckian and daylight loci.

The maximal whiteness perception arose at (0.1947, 0.4599) in the CIE 1976 *u' v'* chromaticity, which is equivalent to a CCT of 7300 K, as predicted by the center of the bivariate Gaussian distribution. Interestingly, the center was slightly shifted towards a higher color temperature, compared to the standard white point D65, which complies with the previous studies on achromatic perception [11, 22]. However, Smet *et al.* [12] and Wang *et al.* [20] reported that maximal whiteness perception arose at around 6600 K, which contradicts the results. With regard to the Duv value, the white perception was centered at 0.0026, which is slightly above the Planckian locus and near the daylight locus. This is in good agreement with the results obtained by Rea and Freyssinier [10] and Chauhan *et al.* [11], who reported positive Duv values for CCTs above 4000 K. However, the results do not agree with those from Ohno and Fein [9] and Smet *et al.* [12], who reported white perception with negative Duv values. As mentioned in the introduction, such inconsistency in results may depend largely upon the specifics of the viewing conditions. This study investigated the white perception of self-luminous mobile display background colors under a dark-adapted condition, in contrast to the previous studies that have investigated white perception in the illumination mode [9, 12, 20].

3. Chromatic-adapted whites

Mobile devices are generally observed in various illuminants, which may differ considerably from the dark surroundings due to chromatic adaptation. Hence, in the second part of the

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study, the effects of ambient illuminants on white perception were investigated. The degree of whiteness was modeled as an error ellipse and a bivariate Gaussian distribution using the ratings of 97 chromaticity points under 11 ambient lightings of various chromaticities.

3.1 Ambient lightings

The study was conducted in a room equipped with an LED luminous ceiling, as shown in Fig. 5(a). The CCTs of the ambient lighting could be controlled by adjusting the *R*, *G*, *B*, and *W* (White) input values. Eleven CCTs were selected to cover the full range of CCTs: 2500, 3000, 4000, 5000, 6000, 7000, 8000, 9000, 10000, 15000, and 20000 K, as shown in Fig. 5(b). The illuminance level was adjusted to approximately 500 to 600 lux, which is a recommended illuminance level for tasks with medium visual requirements [23]. The size of the room was 6.2 m × 3.3 m × 2.5 m, and the walls and a majority of the furniture were off-white. All of the curtains were closed to block off the fluctuations of natural daylight. The colorimetric values of each lighting condition were measured on a horizontal plane at the participants' desk level with a chroma meter (Konica Minolta CL-200), as listed in Table 4.

Table 4. The CCT (K), illuminance (lux), Duv, *u'*, *v'*, and color-rendering index (CRI) of the 11 lightings

Lighting	CCT (K)	Illuminance (lux)	Duv	*u'*	*v'*	CRI
1	2540	607	–0.0008	0.2706	0.5274	79
2	3010	601	–0.0012	0.2506	0.5194	83
3	4074	601	–0.0015	0.2247	0.4983	84
4	5012	597	–0.0006	0.2117	0.4838	89
5	6033	608	0.0005	0.2027	0.4713	90
6	7006	606	0.0003	0.1979	0.4607	92
7	8069	605	–0.0011	0.1954	0.4508	91
8	9023	603	–0.0010	0.1931	0.4445	90
9	10020	602	–0.0005	0.1910	0.4393	87
10	15250	602	0.0002	0.1866	0.4226	89
11	19280	606	0.0009	0.1853	0.4161	88

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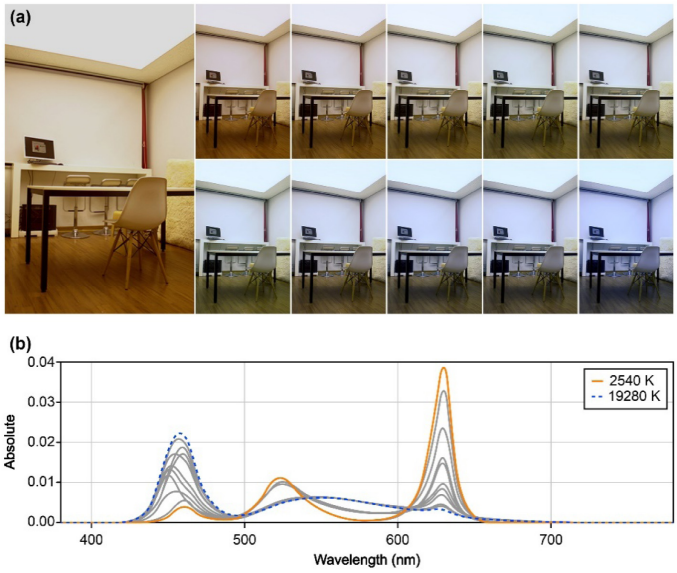

Fig. 5. (a) Experimental room equipped with an LED luminous ceiling; (b) spectral power distributions of the 11 lightings used in the experiments at each CCT condition.

3.2 Procedure

The same group of subjects from the previous experiment participated in this experiment. The specifics of the experimental setting, namely the display stimuli, viewing distance, rating method, and ambient conditions of the room, were consistent with those of the previous study. The subjects were seated in the center of the room, and their full view was completely adapted to the illumination. The 11 lighting conditions were presented in random order. Before each lighting condition, 30 seconds of dark adaptation was performed. Then, 1 minute was given for chromatic adaptation prior to the 97-stimuli evaluation. Each run typically took about 5 to 10 minutes, for a total of about an hour and a half for 1067 ratings (11 lighting conditions × 97 display stimuli).

3.3 Results and discussion

For the analysis, an error ellipse and a bivariate Gaussian distribution were both fitted. First, the chromaticity points that scored five points were fitted into a one-standard-deviation ellipse for each of the 11 lighting conditions, as listed in Table 5.

Table 5. The size of the major and minor axes, the center, the angle of rotation, and the area of each ellipse

Lighting (K)	Major axis	Minor axis	u'	v'	CCT (K)	Duv	Angle (°)	Area (10^{-4})
2540	0.0262	0.0076	0.2050	0.4742	5750	0.0000	59	6.25
3010	0.0252	0.0083	0.2040	0.4751	5769	0.0011	59	6.56
4074	0.0232	0.0074	0.2011	0.4714	6124	0.0018	62	5.42
5012	0.0188	0.0076	0.1969	0.4658	6723	0.0030	66	4.47
6033	0.0178	0.0072	0.1955	0.4636	6970	0.0033	69	4.04
7006	0.0189	0.0072	0.1938	0.4604	7326	0.0036	65	4.28
8069	0.0196	0.0075	0.1932	0.4593	7463	0.0036	65	4.64
9023	0.0173	0.0073	0.1916	0.4557	7894	0.0038	66	3.98
10020	0.0181	0.0082	0.1915	0.4551	7962	0.0037	65	4.67
15250	0.0207	0.0081	0.1908	0.4528	8250	0.0035	66	5.29
19280	0.0230	0.0076	0.1906	0.4523	8311	0.0035	62	5.51

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Secondly, the full data set was modeled with a bivariate Gaussian distribution. The fitting parameters and the centers of each bivariate Gaussian model are summarized in Table 6. The average color difference, delta *u'v'*, between the error ellipse's center and the bivariate Gaussian distribution's center was 0.0053, which is greater than the just-noticeable difference in self-luminous display applications [24]. The average Spearman correlation coefficient was 0.85 ($p < 0.01$), and the average *STRESS* value was 0.10, suggesting that the bivariate Gaussian functions were accurately modeled. Hence, the centers of the bivariate Gaussian distributions were adopted as the chromaticities of maximal whiteness perception.

As seen in Table 6, the coordinates and CCT of the maximal whiteness perception for the 2540 K and 19280 K lighting conditions were (0.2079, 0.4834, 5222 K) and (0.1851, 0.4506, 8986 K), respectively. Within these bounds, a strong correlation was observed: the CCT of the white center increased as the lighting CCT rose ($r = 0.95$, $p < 0.01$). When compared to the dark-adapted white center (0.1947, 0.4599, 7300 K), the chromatic-adapted white centers were shifted towards the chromaticity of the ambient lightings. With regard to the Duv value, it is interesting to note that chromatic-adapted white centers follow a very different trajectory when compared to the Planckian locus. The route connecting 11 white centers is not parallel to the Planckian locus. The Duv value of the center increased from 0.0019 to 0.0078 as the CCT of the center increased ($r = 0.93$, $p < 0.01$), implying that the Duv could be a function of the CCT. The experimental data were compared with the corresponding data predicted by CIECAM02 [25] under mixed chromatic adaptation [26], as shown in Fig. 6. Based on the general trend of these plots, the CIECAM02 prediction shows a better agreement with the bivariate Gaussian centers compared to the error ellipse centers. However, the lower color temperature adaptations lie away from their corresponding CIECAM02 predictions, which is consistent with Hunt's experimental data [27].

Table 6. Fitting parameters $a_{1\text{-}6}$ and the *u'*, *v'*, CCT, and Duv of the center of each bivariate Gaussian distribution

Lighting (K)	a_1	a_2	a_3	a_4	a_5	a_6	*u'*	*v'*	CCT (K)	Duv
2540	2012.73	880.26	0.21	0.48	–714.81	2.90	0.2079	0.4834	5222	0.0019
3010	2709.39	1133.78	0.21	0.48	–964.50	3.04	0.2062	0.4808	5406	0.0019
4074	2898.44	1196.07	0.20	0.48	–820.41	3.10	0.2032	0.4762	5765	0.0022
5012	2983.53	1070.76	0.20	0.47	–553.47	3.22	0.1972	0.4721	6325	0.0052
6033	2892.54	1081.44	0.19	0.47	–546.84	3.16	0.1947	0.4688	6680	0.0059
7006	3017.31	1170.50	0.19	0.46	–639.71	3.04	0.1924	0.4649	7096	0.0064
8069	3146.22	1144.64	0.19	0.46	–642.73	3.05	0.1914	0.4619	7394	0.0062
9023	3302.97	1205.31	0.19	0.46	–796.85	3.05	0.1907	0.4587	7706	0.0056
10020	2969.10	1069.52	0.19	0.46	–638.79	3.11	0.1902	0.4590	7720	0.0061
15250	2329.25	975.62	0.19	0.45	–778.48	2.87	0.1863	0.4544	8466	0.0080
19280	2532.71	1076.44	0.19	0.45	–939.14	2.91	0.1851	0.4506	8986	0.0078

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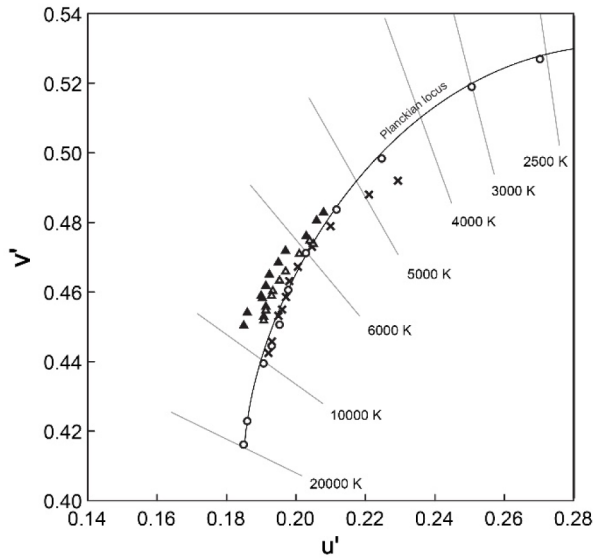

Fig. 6. The experimental data were compared with the corresponding data predicted by CIECAM02. The centers of error ellipses and bivariate Gaussian distributions are plotted with hollow and filled triangles, respectively. The ambient illuminants and CIECAM02 predictions are marked with circles and crosses.

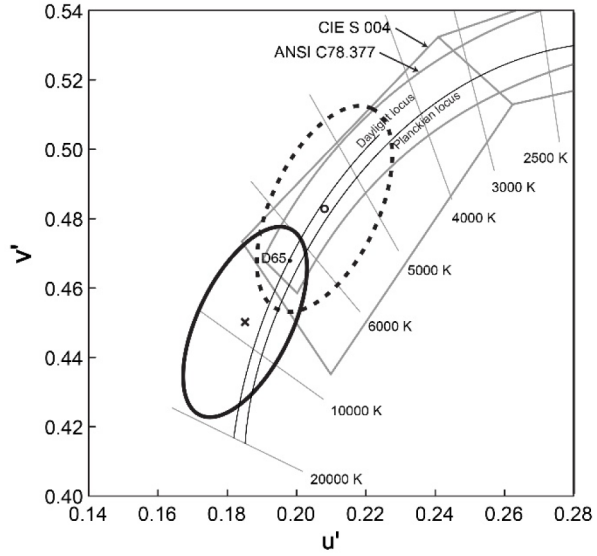

Fig. 7. 50% bivariate Gaussian ellipses fitted for 2540 K lighting plotted as a dashed line with a circle center, and 19280 K lighting plotted as a solid line with a cross center. The ANSI C78.377 and CIE S 004 are also shown, along with the Planckian and daylight loci.

The 50% bivariate Gaussian ellipses of the low- and high-CCT end-lighting conditions—2540 K and 19280 K, respectively—are plotted in Fig. 7. The directions of the major axis of both ellipses are aligned with the Planckian locus, which is in good agreement with the previous experiment. The 50% bivariate Gaussian ellipse for the 2540 K lighting condition, plotted as a dashed line, encompassed 3995 to 7479 K in CCT and −0.0101 to 0.0144 in Duv. For the 19280 K lighting condition, the area encompassed 6179 to 15131 K in CCT and −0.0038 to 0.0196 in Duv. Although the white region of the 2540 K lighting condition

overlapped the high CCT regions of ANSI C78.377 and the CIE class A white boundary, the white region of the 19280 K lighting condition was far from the standard boundaries. The data presented here suggest that self-luminous displays that meet the standards will probably only appear white under limited viewing conditions. Hence, the chromaticity points within the intersection of those regions, ranging from 6179 to 7479 K in CCT and from −0.0038 to 0.0144 in Duv, are expected to appear moderately white under any lighting condition. These findings might be applied as the basis for guidance on the white point adjustment of self-luminous mobile display devices.

4. General discussion

The chromaticity of white was investigated under dark-adapted and chromatic-adapted conditions. The dark-adapted white region encompassed a rather large area, which was shifted towards a higher color temperature and slightly above the Planckian locus compared to the current standards. Although earlier studies have also reported that the perceptually preferred white could have a slightly bluish tint [11, 22, 28], until recently, many studies have relied on the underlying assumption that 6500 K is the highest boundary of white perception [9, 10]. With regard to Duv, although there is some inconsistency in its exact value among previous studies [9–13], it is now quite apparent that the Duv is also a strong determinant factor of white perception. Additionally, white perception is highly dependent on the chromaticity of the ambient illuminant, although most studies have focused on dark-adapted white perception. Combined, future works should not be bound by the set of underlying assumptions for white perception and should leave possibilities open in designing experiments.

However, this study's experimental conditions also have some prevalent limitations. First, the stimuli were confined to a reading article. However, white perception is likely to be image dependent; hence, supplementary studies with various images are necessary. Moreover, the illuminance of the ambient illuminant was fixed at approximately 600 lux in the chromatic-adapted experiment. As the effect of an illuminant's chromaticity increases with its intensity [29], future work is necessary to verify the applicability of the results in various viewing conditions. Additionally, as mentioned in the introduction, the standards of white points differ substantially depending on the country [30]. Hence, it would also be valuable to evaluate whether any cultural effects exist on the perception of white. Lastly, although Smet *et al.* [12] and Walraven and Werner [31] confirmed that white perception is luminance invariant, more in-depth studies would be worthwhile to investigate the effect of luminance in combination with chromaticity. Otherwise, the maximal luminance could be obtained for a target chromaticity using the optimal converting point suggested by Hsieh *et al.* [32]. Nonetheless, the present study builds upon and extends earlier studies, with increased insights that could act as good stepping stones for future deliberations on white perception.

5. Conclusion

The purpose of this study was to investigate the white perception of a self-luminous mobile display under dark-adapted and chromatic-adapted conditions. The whiteness ratings on 97 chromaticity points were fitted into an error ellipse and a bivariate Gaussian distribution. The results showed that CCT alone is not a suitable designation of white perception. Dark-adapted white perception was located slightly above the Planckian locus and was approximately centered around 7300 K. Moreover, white perception was highly dependent on the chromaticity of the ambient illuminant. The route connecting the chromatic-adapted white centers was not parallel to the Planckian locus, implying that Duv could be a function of CCT. The self-luminous displays that meet the current standards would probably not be perceived as white under some viewing conditions; hence, the present study suggests a white region from 6179 to 7479 K in CCT and from −0.0038 to 0.0144 in Duv. Although further research is necessary, the study is expected to have properly estimated the psychophysical aspects of users viewing white on mobile display devices.

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