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White appearance of a tablet display under different ambient lighting conditions

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Abstract: In comparison to the great efforts made on the enhancement of image quality for tablet displays, little attention has been paid on the concept of white point. Given the increasing popularity of the light sources with chromaticities off the Planckian locus and color-tunable LED lighting, it is important to investigate human's white perception of tablet display under different ambient lighting conditions. This study investigated the white appearance of a tablet display under 17 ambient lighting conditions, including a dark condition, seven conditions with chromaticities on the Planckian locus, and nine conditions with chromaticities off the Planckian locus, (i.e., D_{uv} = + 0.02, –0.02, and –0.04). It was found that both the white appearance boundary defined by the fitted one-standard-deviation error ellipse and the whitest stimulus rated by the observers or identified by the bivariate Gaussian distribution were different under the various ambient lighting conditions. The optimization based on the whitest stimulus under each ambient lighting condition suggested a lower degree of chromatic adaptation under the conditions with a lower Correlated Color Temperature (CCT). For the conditions with a same CCT, a D_{uv} of –0.02 was found to provide a higher degree of chromatic adaptation than D_{uv} values of + 0.02 and –0.04.

OCIS codes: (330.0330) Vision, color, and visual optics; (330.1730) Colorimetry; (330.5510) Psychophysics; (330.7320) Vision adaptation.

References and links

1. L. C. Ou, P. L. Sun, H. P. Huang, and M. R. Luo, "Visual comfort as a function of lightness difference between text and background: A cross-age study using an LCD and a tablet computer," Color Res. Appl. **40**(2), 125–134 (2015).
2. H. P. Huang, L. C. Ou, and Y. Yuan, "Effects of age and ambient illuminance on visual comfort for reading on a mobile device," Color Res. Appl. **42**(3), 352–361 (2017).
3. J. Wu, L. Zhang, C. Chen, G. Marcu, W. Chaohao, M. Xu, R. Motta, W. Chen, and J. Z. Zhong, "Ambient light adaptive displays," (Google Patents, 2016).
4. M. Wei, Y. Wang, S. Ma, and M. R. Luo, "Chromaticity and characterization of whiteness for surface colors," Opt. Express **25**(23), 27981–27994 (2017).
5. K. A. G. Smet, "Two neutral white illumination loci based on unique white rating and degree of chromatic adaptation," Leukos, published online (2017).
6. K. A. Smet, G. Deconinck, and P. Hanselaer, "Chromaticity of unique white in illumination mode," Opt. Express **23**(10), 12488–12495 (2015).
7. K. A. Smet, D. Geert, and H. Peter, "Chromaticity of unique white in object mode," Opt. Express **22**(21), 25830–25841 (2014).
8. M. Wei, S. Ma, Y. Wang, and M. R. Luo, "Evaluation of whiteness formulas for FWA and non-FWA whites," J. Opt. Soc. Am. A **34**(4), 640–647 (2017).
9. L. M. Hurvich and D. Jameson, "A psychophysical study of white. I. Neutral adaptation," J. Opt. Soc. Am. **41**(8), 521–527 (1951).
10. K. Honjyo and M. Nonaka, "Perception of white in a 10° field," J. Opt. Soc. Am. **60**(12), 1690–1694 (1970).
11. A. Valberg, "A method for the precise determination of achromatic colours including white," Vision Res. **11**(2), 157–160 (1971).

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12. J. Walraven and J. S. Werner, "The invariance of unique white; a possible implication for normalizing cone action spectra," Vision Res. **31**(12), 2185–2193 (1991).
13. M. S. Rea and J. P. Freyssinier, "White lighting," Color Res. Appl. **38**(2), 82–92 (2013).
14. I. G. Priest, "The spectral distribution of energy required to evoke the gray sensation," J. Opt. Soc. Am. **5**(2), 205–209 (1921).
15. H. Helson and W. C. Michels, "The effect of chromatic adaptation on achromaticity," J. Opt. Soc. Am. **38**(12), 1025–1032 (1948).
16. M. Langford and E. Bilissi, *Langford's Advanced Photography: The Guide for Aspiring Photographers* (Taylor & Francis, 2011).
17. A. Van Hurkman, *Color Correction Handbook: Professional Techniques for Video and Cinema* (Pearson Education, 2013).
18. K. Choi and H.-J. Suk, "Assessment of white for displays under dark- and chromatic-adapted conditions," Opt. Express **24**(25), 28945–28957 (2016).
19. E. E. Dikel, G. J. Burns, J. A. Veitch, S. Mancini, and G. R. Newsham, "Preferred chromaticity of color-tunable LED lighting," Leukos **10**(2), 101–115 (2014).
20. CIE, "Method of Measuring and Specifying Color Rendering Properties of Light Sources, 3rd.edition," in CIE 13.3:1995, CIE, Vienna, Austria, (1995).
21. P. A. García, R. Huertas, M. Melgosa, and G. Cui, "Measurement of the relationship between perceived and computed color differences," J. Opt. Soc. Am. A **24**(7), 1823–1829 (2007).
22. W. Xu, M. Wei, A. K. G. Smet, and Y. Lin, "The prediction of perceived color differences by color fidelity metrics," Light. Res. Technol. **49**(7), 805–817 (2016).
23. R. Shamey, L. M. Cárdenas, D. Hinks, and R. Woodard, "Comparison of naïve and expert subjects in the assessment of small color differences," J. Opt. Soc. Am. A **27**(6), 1482–1489 (2010).
24. K. A. G. Smet, W. R. Ryckaert, M. R. Pointer, G. Deconinck, and P. Hanselaer, "Colour appearance rating of familiar real objects," Color Res. Appl. **36**(3), 192–200 (2011).
25. M. R. Luo, G. Cui, and C. Li, "Uniform color spaces based on CIECAM02 color appearance model," Color Res. Appl. **31**(4), 320–330 (2006).
26. K. A. G. Smet, Q. Zhai, M. R. Luo, and P. Hanselaer, "Study of chromatic adaptation using memory color matches, Part I: neutral illuminants," Opt. Express **25**(7), 7732–7748 (2017).
27. K. A. G. Smet, Q. Zhai, M. R. Luo, and P. Hanselaer, "Study of chromatic adaptation using memory color matches, Part II: colored illuminants," Opt. Express **25**(7), 8350–8365 (2017).
28. Q. Zhai, M. R. Luo, P. Hanselaer, and A. K. G. Smet, "Modeling incomplete chromatic adaptation and color contrast using memory color," in *Proceedings of 24th Color and Imaging Conference* (2016), pp. 82–86.
29. CIE, "Colorimetry Part 6: CIEDE2000 Color-Difference Formula," in ISO/CIE 11664–6:2014(E), CIE, Vienna, Austria, (2014).

1. Introduction

Tablets and smart phones are becoming necessities in our daily life; they are used under various lighting conditions, from dark condition at night to very bright condition under daylight. Considerations have been given to different characteristics of the displays of tablets and smart phones, such as brightness, text-background luminance contrast, color gamut, and color saturation [1, 2], to enhance the visual comfort or the user experience. Manufacturers also tried to change the white point of the display under different ambient lighting conditions [3], as the ambient lighting affects human's perception to the color stimuli on the display.

White, a color that has a certain level of lightness and without any hue, can be associated to the color of surfaces, illuminants, and displays. The perception of white, however, has been found to be significantly different for different media and viewing modes [4–15]. When investigating the image quality of displays, the white points of D50, D65, and D93 were commonly employed, as they are the typical white points in imaging and photography industries and are recommended in various standards [16, 17]. The concept of the white point of a display, however, was seldom investigated, except by Choi and Suk [18]. Choi and Suk [18] studied the white appearance of a 9.7-inch tablet under 11 ambient lighting conditions and a dark condition. The tablet, however, had a white boundary, which may affect the evaluation of the white appearance made by the observers. Moreover, all the 11 ambient lighting conditions had chromaticities on the Planckian locus, which may limit the applicability of the findings, given the popularity of sources with chromaticities off the Planckian locus [13, 19] and color-tunable LED lighting.

In this study, we used a 9.7-inch tablet with a dark boundary to investigate the white appearance of the display under 17 ambient lighting conditions, including a dark condition,

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seven conditions with chromaticities on the Planckian locus, and nine conditions with chromaticities off the Planckian locus (i.e., D_{uv} = + 0.02, −0.02, and −0.04), with an aim to further understand human's perception to white stimuli and chromatic adaptation under various lighting conditions using the boundary of white appearance and the whitest stimulus under each ambient lighting condition.

2. Methods

The experimental protocol and procedure were approved by the Institutional Review Board.

2.1 Apparatus

The experiment was carried out using a viewing booth, with dimensions of 60 cm × 60 cm × 60 cm. The interiors of the viewing booth were painted with Munsell N7 spectrally neutral paint. A 14-channel spectrally tunable LED lighting device (LEDCube) was placed above the booth to produce a uniform illumination. The front side of the booth was partially covered, with the bottom 45 cm open, preventing observers from seeing the lighting device. A 45° viewing table was placed at the center of the viewing booth, with an iPad Air 2 being placed on it, as shown in Fig. 1. A chin rest was mounted outside the booth, centered on the opening, so that the observers perpendicularly viewed the screen with a field of view (FOV) around 44°. The intensities of the 14 LED channels whose peak wavelengths covered from 350 to 700 nm can be individually adjusted. During the experiment, no general illumination was provided in the experimental space.

Fig. 1. Photograph taken from the observer's eye position. The observers fixed their chin on a chin rest.

2.2 Ambient lighting conditions and tablet stimuli

There were 17 ambient lighting conditions, including one dark condition, seven conditions with chromaticities on the Planckian locus, and nine conditions with chromaticities off the Planckian locus. Figure 2(a) shows the chromaticity coordinates of the ambient lighting conditions in CIE 1976 UCS using the CIE 1964 10° Color Matching Functions (CMFs), which were calculated using the spectral power distribution (SPD) measured with a calibrated JETI specbos 1211™ spectroradiometer and a reflectance standard being placed at center of the viewing table. The intensities of the 14 channels were carefully adjusted for each lighting condition to maximize the CIE General Color Rendering Index (CRI R_a) [20]. Table 1 summarizes the colorimetric characteristics of the ambient lighting conditions. All the ambient lighting conditions were calibrated to provide an illuminance level of 1000 ± 30 lx at the center of the viewing table using a calibrated Minolta T-10 illuminance meter.

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The iPad had a default white point at 6850 K with a D_{uv} of + 0.0050. The RGB values of the iPad were adjusted to produce 76 stimuli, whose chromaticities were uniformly distributed in CIE1976 UCS and luminance levels were at 235 ± 10 cd/m^2, as shown in Fig. 2(b), measured using a calibrated Xrite i1 Pro spectrophotometer. The entire display was covered by one stimulus, as shown in Fig. 1.

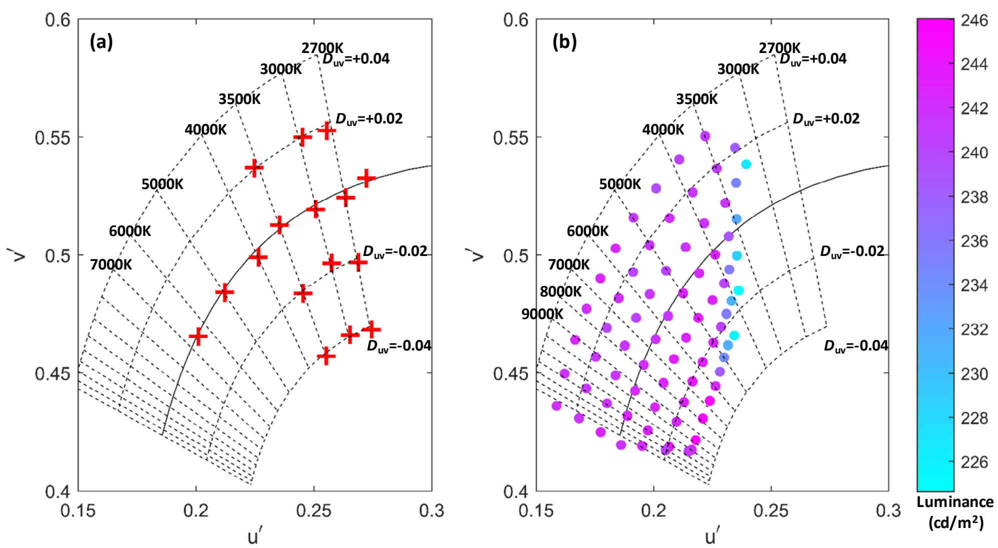

Fig. 2. The chromaticity coordinates of the ambient lighting conditions and the stimuli that were presented on the iPad in CIE1976 UCS. (a) the chromaticity coordinates of the ambient lighting conditions; (b) the chromaticity coordinates and the luminance of the stimuli that were presented on the iPad.

Table 1. Colorimetric characteristics of the 17 ambient lighting conditions.

Nominal CCT (K)	Nominal D_{uv}	CCT (K)	D_{uv}	CRI R_a	IES R_f	IES R_g
Dark	-	-	-	-	-	-
2500	0	2495	+ 0.0009	83.1	82.0	98.0
2700	−0.04	2682	−0.0411	91.4	50.9	119.7
2700	−0.02	2689	−0.0213	89.8	69.3	110.7
2700	0	2692	−0.0022	94.5	89.0	106.4
2700	+ 0.02	2741	0.0182	81.7	65.1	75.1
3000	−0.04	2976	−0.0397	90.7	55.8	118.3
3000	−0.02	2983	−0.0180	92.2	88.7	105.3
3000	0	3009	−0.0013	90.9	90.4	96.2
3000	+ 0.02	2959	+ 0.0197	74.6	78.4	80.5
3500	−0.04	3493	−0.0410	89.3	59.8	116.3
3500	−0.02	3507	−0.0208	92.0	81.5	107.8
3500	0	3493	+ 0.0010	91.9	88.6	95.4
3500	+ 0.02	3551	+ 0.0202	89.0	84.6	88.4
4000	0	3995	−0.0022	96.4	93.7	103.0
5000	0	4980	−0.0008	96.3	95.2	103.1
6500	0	6469	−0.0005	87.5	86.2	97.0

2.3 Observers and evaluations of white appearance on the iPad

Sixty-three naïve observers (44 males and 19 females) between 18 and 27 years of age (mean = 21, std. dev. = 1.9) participated in this study. All the observers had normal color vision, as tested using the Ishihara Color Vision Test. None of the observers had knowledge about the study. Each observer evaluated the white appearance of 264 stimuli under three ambient lighting conditions, with 86 stimuli (i.e., 76 stimuli + 10 stimuli on the Planckian locus for

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evaluating intra-observer variation) under each lighting condition. Each ambient lighting condition was evaluated by 10 or 11 observers.

For each stimulus, the observers were asked to make two judgements—a forced-choice judgment about whether the color appearance of the stimulus can be classified as white (i.e., either "yes" or "no") and a magnitude of estimation about the whiteness percentage of the stimulus (i.e., 100% means a pure white and 0% means purely chromatic).

2.4 Experimental procedures

Upon arrival, the observer completed the general information survey and the Ishihara Color Vision Test. Then the experimenter explained the experimental procedure and tasks to the observer and escorted the observer to the viewing booth. The observer was seated in front of the viewing booth with the chin being placed on a rest for fixing the viewing geometry. Next the experimenter read the instructions and answered the questions raised by the observer.

Under each ambient lighting condition, the observer was asked to look into the booth for three minutes for chromatic adaptation. Then the experimenter placed the iPad on the viewing table (note: the iPad was switched on for 30 minutes prior to the experiment for stabilization). A stimulus was then presented on the iPad for five seconds, during which the observer was asked to look at the display. After the five seconds, the display became black and the observer was prompted to make the two judgements, as described in Section 2.3. The 86 stimuli were presented in a random order and the same procedure was repeated for all the 86 stimuli under each ambient lighting condition. After completing the evaluation of all the 86 stimuli, the observer took a three-minute washout period and then returned to the viewing booth. Same procedure was repeated for the other two ambient lighting conditions. The order of the ambient lighting conditions were also randomized between the observers.

Before evaluating the 86 stimuli under the first ambient lighting condition, the observer evaluated five stimuli for getting familiar with the experiment procedure. The entire experiment took around 45 minutes for each observer.

3. Results and discussions

3.1 Intra- and inter-observer variations, correlation between the two judgements

The intra- and inter-observer variations were characterized using the Standardized Residual Sum of Squares (*STRESS*) [21], which has been widely used in color appearance evaluations. Each observer evaluated 10 identical stimuli twice under each ambient lighting condition, with a total of 30 stimuli being evaluated twice. The intra-observer variation was characterized by comparing the two sets of the whiteness percentage values for these 30 stimuli rated by each observer. Figure 3 shows the histogram of the *STRESS* values of the 63 observers, with a mean of 33.56, which was comparable to past studies [4, 8, 22, 23].

The inter-observer variation was characterized by comparing the whiteness percentage values of the 76 stimuli rated by each observer and the average whiteness percentage values of the 76 stimuli rated by the observers (i.e., an average observer) under each ambient lighting condition. Table 2 summarizes the *STRESS* values of the 17 ambient lighting conditions, with a mean of 37.58, which was also comparable to other studies. No systematic relationship between the inter-observer variations and ambient lighting conditions can be found in Table 2.

The two judgements made by the observers were positively correlated; stimuli that were more frequently judged as white were rated to have higher whiteness percentage values, as shown in Fig. 4.

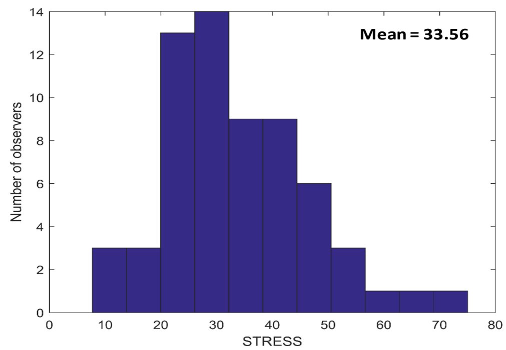

Fig. 3. The histogram of the *STRESS* values of the 63 observers for characterizing the intra-observer variations.

Table 2. The *STRESS* values of the 17 ambient lighting conditions for characterizing the inter-observer variations.

CCT	Dark	2500	2700	2700	2700	2700	3000	3000	3000
D_{uv}		0	–0.04	–0.02	0	+ 0.02	–0.04	–0.02	0
STRESS	46.14	28.73	34.21	34.75	36.23	31.37	28.46	31.61	43.73
CCT	3000	3500	3500	3500	3500	4000	5000	6500	
D_{uv}	+ 0.02	–0.04	–0.02	0	+ 0.02	0	0	0	
STRESS	33.89	33.25	39.71	38.34	35.87	47.23	48.52	46.74	

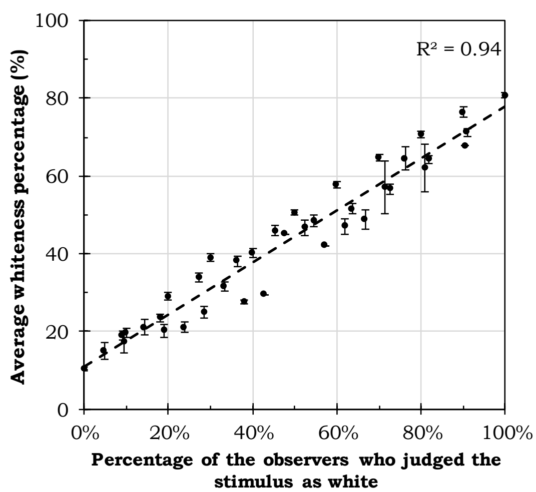

Fig. 4. Correlation between the two judgements made by the observers

3.2 Boundary of white appearance under each ambient lighting condition

For each ambient lighting condition, the one-standard-deviation error ellipse was fitted in CIE 1976 UCS, as shown in Fig. 5, using the forced-choice judgements made by the observers to define the boundary of white appearance, with the parameters being summarized in Table 3.

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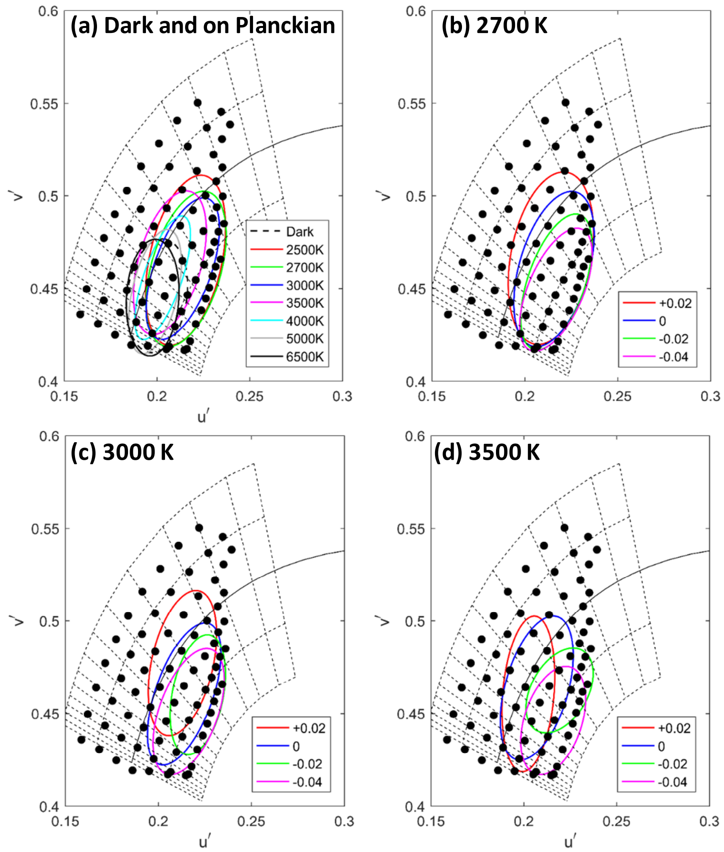

Fig. 5. The one-standard-deviation error ellipses for the iPad stimuli that were judged as white under different ambient lighting conditions (a) the dark ambient condition and the conditions with chromaticities on the Planckian locus from 2500 to 6500 K; (b) the 2700 K ambient lighting conditions; (c) the 3000 K ambient lighting conditions; (d) the 3500 K ambient lighting conditions.

For the ambient lighting conditions with chromaticities on the Planckian locus, the ellipse shifted with the increase of CCT along the Planckian locus. The boundary ellipses for the lighting conditions with CCT above 3500 K were generally around the Planckian locus; while those for the lighting conditions with CCT below 3500 K tended to be below the Planckian locus, as shown in Fig. 5(a).

For the ambient lighting conditions with same CCT but different D_{uv} values, the boundary ellipses shifted perpendicularly to the Planckian locus with the change of D_{uv}, as shown in Figs. 5(b)-5(d).

Table 3. Parameters of the one-standard-deviation error ellipses, shown in Fig. 6, for defining the white boundary under each ambient lighting condition

Ambient lighting condition		Fitted one-standard-deviation ellipse for whiteness boundary				
CCT	D_{uv}	(u_c',v_c')	Long-axis	Short-axis	Orientation	Area
Dark		(0.2001,0.4460)	0.0309	0.0161	82.68°	0.0016
2500	0	(0.2154,0.4652)	0.0469	0.0195	77.52°	0.0029
2700	–0.04	(0.2167,0.4494)	0.0355	0.0148	66.82°	0.0017
2700	–0.02	(0.2170,0.4535)	0.0384	0.0154	71.02°	0.0019
2700	0	(0.2157,0.4605)	0.0432	0.0188	74.11°	0.0026
2700	+ 0.02	(0.2140,0.4663)	0.0471	0.0216	79.39°	0.0032

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3000	−0.04	(0.2163,0.4511)	0.0356	0.0157	70.01°	0.0018
3000	−0.02	(0.2212,0.4602)	0.0328	0.0137	78.97°	0.0014
3000	0	(0.2139,0.4606)	0.0402	0.0154	70.54°	0.0019
3000	+ 0.02	(0.2130,0.4772)	0.0400	0.0165	77.33°	0.0021
3500	−0.04	(0.2158,0.4463)	0.0302	0.0155	71.91°	0.0015
3500	−0.02	(0.2193,0.4624)	0.0248	0.0152	60.04°	0.0012
3500	0	(0.2070,0.4638)	0.0400	0.0170	74.14°	0.0021
3500	+ 0.02	(0.2024,0.4606)	0.0420	0.0138	85.11°	0.0018
4000	0	(0.2031,0.4557)	0.0351	0.0103	71.09°	0.0011
5000	0	(0.1990,0.4482)	0.0342	0.0123	77.12°	0.0013
6500	0	(0.1976,0.4451)	0.0315	0.0142	86.70°	0.0014

3.3 The whitest stimulus and modeling of the whiteness percentage under each ambient lighting condition

The chromaticity coordinates of the whitest stimulus which was rated to have the highest whiteness percentage value under each ambient lighting condition are highlighted with red circles in Fig. 6.

The whiteness percentage value rated by the observers were used to fit a bivariate Gaussian model [24] to characterize the whiteness percentage of a stimulus $W(u',v')$, as described in Eq. (1).

$$W\left(u',v'\right) = a_1 + a_2 \cdot exp\left(-\frac{1}{2}d^2\left(u',v'\right)\right) \quad (1)$$

where $d^2\left(u',v'\right) = \left(X - X_c\right)^T \cdot \Sigma^{-1} \cdot \left(X - X_c\right)$, X is (u',v') of the stimulus, X_c is the estimated center (u_c',v_c'), representing the estimated whitest chromaticities, and Σ is the 2-by-2 covariance matrix.

The bivariate Gaussian distribution $W(u',v')$ was fitted for each ambient lighting condition, with Fig. 7 illustrating the distribution under the dark condition as an example. Table 4 summarizes the whitest stimulus (u_c',v_c'), the corresponding CCT and D_{uv} based on the fitted Gaussian distribution, and the Pearson correlation coefficient between the estimated whiteness percentage $W(u',v')$ and the rated whiteness percentage for all the stimuli under each ambient lighting condition, with an average of 0.949.

It can be observed from Fig. 6 that the chromaticity coordinates of the whitest stimulus estimated by the fitted bivariate Gaussian distribution and rated by the observers under each ambient lighting condition were very close.

Research Article | Vol. 26, No. 4 | 19 Feb 2018 | OPTICS EXPRESS 5026

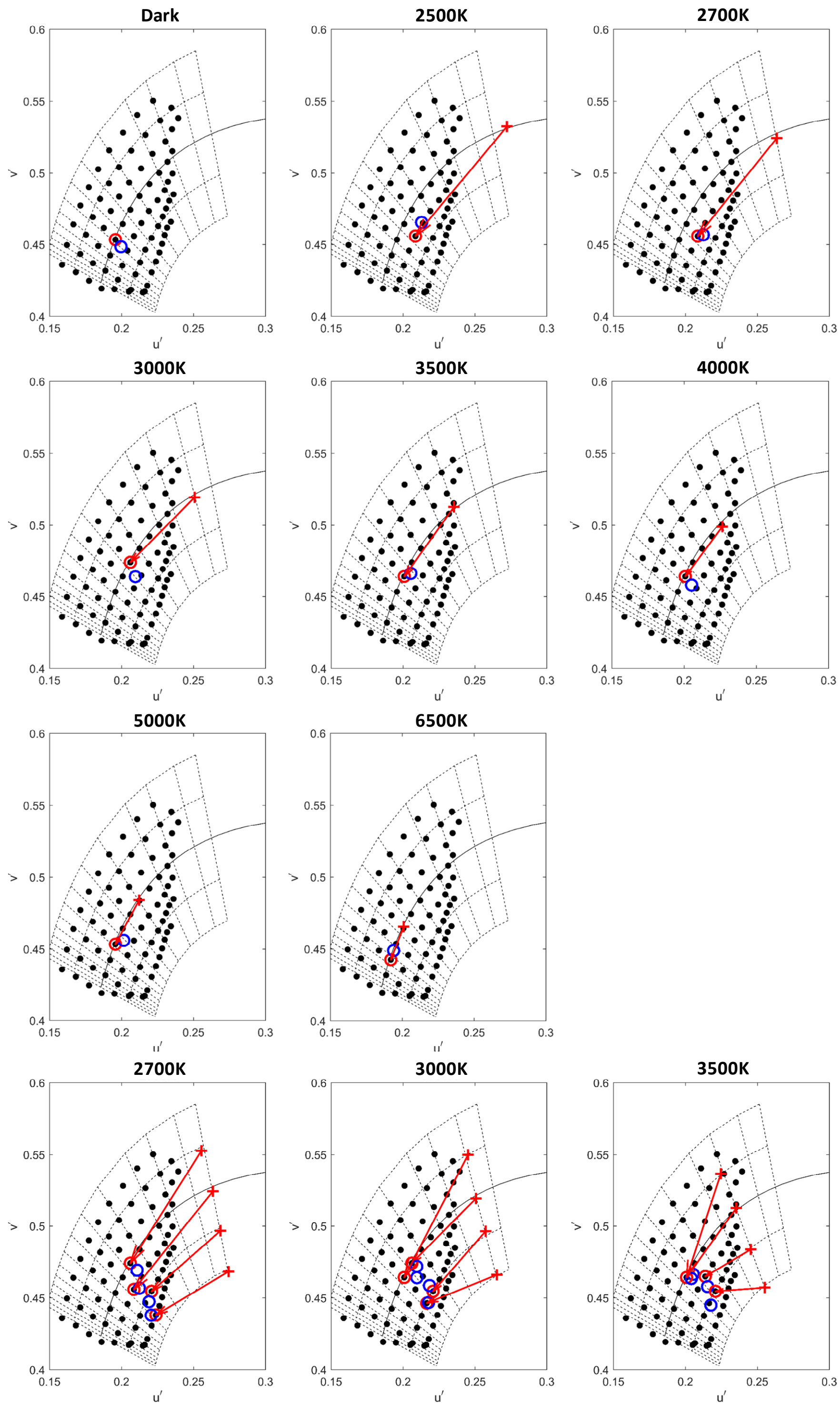

Fig. 6. The chromaticity coordinates of the whitest stimulus rated by the observers (labeled with red circle) and estimated by the fitted bivariate Gaussian distribution $W(u',v')$ (labeled with blue circle) and the chromaticity coordinates of the ambient lighting (labeled with red cross).

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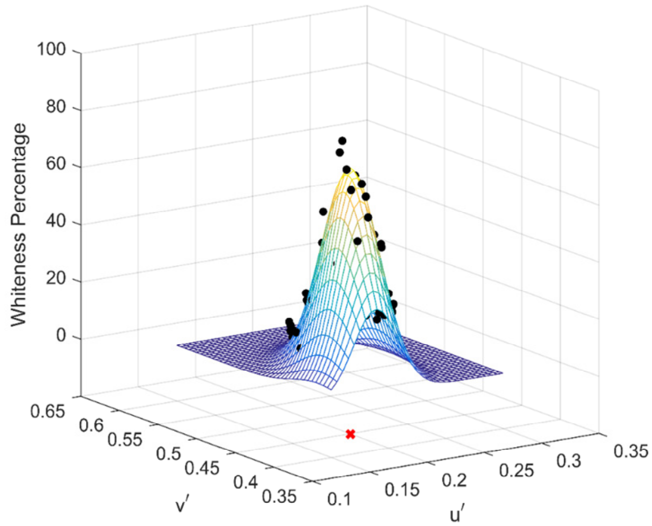

Fig. 7. The fitted bivariate Gaussian distribution $W(u',v')$ for estimating the degree of whiteness when the ambient lighting condition was dark. Same procedure was followed for each ambient lighting condition with the estimated center (u_c',v_c') being labeled with a red dot. Table 4 summarizes the (u_c',v_c') and the corresponding CCT and D_{uv}.

Table 4. The estimated chromaticity coordinates of the whitest stimulus using the fitted bivariate Gaussian distribution and the corresponding CCT and D_{uv} and the Pearson correlation coefficient between the whiteness percentage values estimated using the fitted bivariate Gaussian distribution and rated by the observers under each ambient lighting condition.

Ambient lighting condition		Fitted bivariate Gaussian distribution $W(u',v')$			
CCT	D_{uv}	(u_c',v_c')	CCT	D_{uv}	Correlation coefficient
Dark		(0.1996, 0.4485)	7924	–0.0055	0.963
2500	0	(0.2129, 0.4654)	5693	–0.0099	0.947
2700	–0.04	(0.2206, 0.4380)	7004	–0.0270	0.993
2700	–0.02	(0.2191, 0.4474)	6335	–0.0222	0.986
2700	0	(0.2124, 0.4568)	6211	–0.0131	0.958
2700	+ 0.02	(0.2108, 0.4693)	5635	–0.0066	0.894
3000	–0.04	(0.2177, 0.4468)	6498	–0.0213	0.983
3000	–0.02	(0.2184, 0.4586)	5680	–0.0170	0.979
3000	0	(0.2096, 0.4641)	5975	–0.0079	0.943
3000	+ 0.02	(0.2095, 0.4719)	5593	–0.0044	0.902
3500	–0.04	(0.2177, 0.4450)	6642	–0.0220	0.976
3500	–0.02	(0.2154, 0.4579)	5929	–0.0150	0.976
3500	0	(0.2054, 0.4664)	6123	–0.0036	0.941
3500	+ 0.02	(0.2041, 0.4635)	6379	–0.0037	0.876
4000	0	(0.2052, 0.4582)	6647	–0.0067	0.944
5000	0	(0.2015, 0.4561)	7082	–0.0044	0.940
6500	0	(0.1940, 0.4489)	8395	–0.0005	0.933

When there was no ambient lighting, the stimulus with a CCT of 7500 and a D_{uv} of 0 was rated to be the whitest in this study, which was consistent to a recent study [18]. The change of the whitest stimulus under the ambient lighting conditions was similar to that of the boundary ellipse described in Section 3.2. When the ambient lighting conditions had chromaticities on the Planckian locus and CCT above 3000 K, the whitest stimulus was also on the Planckian locus, while when the CCT was below 3000 K, the whitest stimulus was below the Planckian locus. For the ambient lighting conditions with a same CCT, the shift of the whitest stimulus under different D_{uv} levels was perpendicular to the Planckian locus.

3.4 Degree of chromatic adaptation

Taking the lower uniformity of CIE 1976 UCS into consideration, the chromaticity coordinates of the whitest stimulus under each ambient lighting condition were transformed to CAM02-UCS [25], which is the most uniform color space and embeds a chromatic adaptation transform (i.e., CAT02), with an assumption of complete chromatic adaptation and the degree of chromatic adaptation factor *D* being set to 1, as shown in Fig. 8. If an observer is completely adapted to a lighting condition, the whitest stimulus and the lighting condition should have the same chromaticity coordinates in any color space, which should be located at the origin (0,0) in CAM02-UCS. None of the stimulus, however, had the chromaticities around the origin, as shown in Fig. 8, suggesting a lower degree of chromatic adaptation under these ambient lighting conditions. In contrast, the chromaticities of the whitest stimuli under various lighting conditions were generally around the origin in the *a*'-*b*' plane of CAM02-UCS in a recent study [4] that focused on the whiteness appearance of surface colors. Such a difference was likely due to surface versus self-luminous colors, with a higher degree of chromatic adaptation under surface colors.

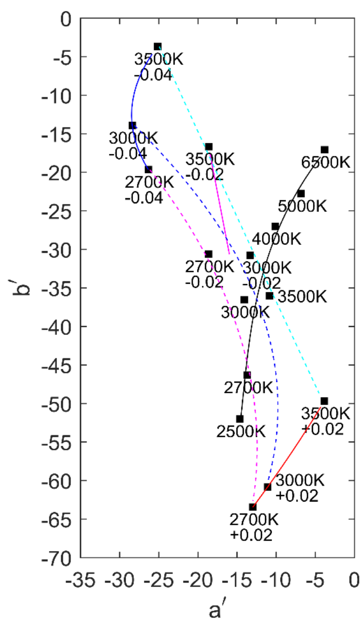

Fig. 8. The chromaticity coordinates (*a*',*b*') of the whitest stimulus under each ambient lighting condition in CAM02-UCS, with the solid lines for the ambient lighting conditions with a same D_{uv} and the dash lines for those with a same CCT.

For the ambient lighting conditions with a same D_{uv} level, the lower the CCT the further the distance between the chromaticities of the whitest stimulus and the origin, as shown by the solid curves in Fig. 8; for the ambient lighting conditions with a same CCT level, the chromaticities of the whitest stimulus were furthest to the origin when the D_{uv} was + 0.02, as shown by the dotted curves in Fig. 8.

Given the smallest chromaticity difference between the whitest stimulus and the ambient lighting in Fig. 6 and the smallest distance to the origin in Fig. 8, the 6500 K ambient lighting condition was selected as a reference for investigating the degree of chromatic adaptation under other lighting conditions. Based on past studies [26–28], the 6500 K ambient lighting condition was also believed to provide the highest degree of chromatic adaptation in this study. Using the whitest stimulus under the 6500 K ambient lighting condition as the reference, the whiteness percentage of the whitest stimulus under each ambient lighting

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condition should be negatively correlated to the color difference between the whitest stimulus under that ambient lighting condition and that under the 6500 K, with a larger color difference being associated with a lower whiteness percentage value. Thus, the degree of chromatic adaptation *D* under each ambient lighting condition, in relative to that under the 6500 K lighting condition, was optimized to minimize the Pearson correlation coefficient between the whiteness percentage value of the whitest stimulus under each lighting condition rated by the observers and the calculated color difference ΔE_{00} [29] between the whitest stimulus under each lighting condition and that under the 6500 K lighting condition.

The optimized *D* values, in relative to that under the 6500 K, are shown in Fig. 9. The trend for the conditions with chromaticity coordinates on the Planckian locus was similar to that found in a recent study [28], with the 4000 and 5000 K lighting conditions had a similar degree of chromatic adaptation as the 6500 K condition. For the ambient lighting conditions with chromaticities off the Planckian locus, a negative D_{uv} tended to produce a higher degree of chromatic adaptation, with a D_{uv} of –0.02 having the highest degree. Such a finding corroborates to our knowledge that human’s visual system cannot adapt to the conditions with chromaticities far away from the Planckian locus. It should be mentioned that the chromaticity coordinates of the whitest stimulus under the ambient lighting condition with a CCT of 2700 K and a D_{uv} of –0.04 were at the boundary of all the stimuli. This whitest stimulus could be due to the limited region covered by the stimuli and could cause the optimized degree of chromatic adaptation, pointed by the arrow in Fig. 9, inaccurate, which should be considered in future studies.

To further understand the degree of chromatic adaptation under different illumination conditions, it will be worthwhile to further increase the CCT of the ambient illumination and to include more chromaticities for both the ambient lighting conditions and the display stimuli in future studies.

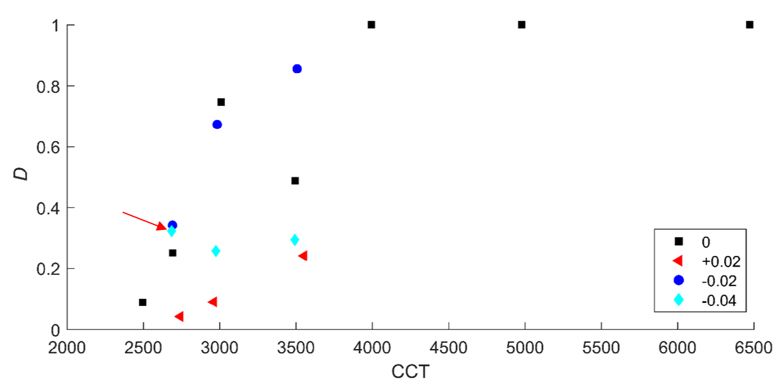

Fig. 9. The optimized degree of chromatic adaptation *D* under each ambient lighting condition. The point highlighted by the arrow represents the ambient lighting condition with a CCT of 2700 K and a D_{uv} of –0.02 could be due to the experimental limitation, as explained in Section 3.4.

4. Conclusions

A psychophysical experiment was carried out to investigate the white appearance of a tablet display (i.e., an iPad Air 2) under different ambient lighting conditions. Sixty-three observers with normal color vision evaluated the white appearance of 86 stimuli (i.e., 76 stimuli + 10 repeated stimuli) under 17 ambient lighting conditions (one dark condition, seven conditions with chromaticities on the Planckian locus, and nine conditions with chromaticities off the Planckian locus); with each ambient lighting condition being judged by 10 or 11 observers.

The one-standard-deviation error ellipse and the bivariate Gaussian distribution were fitted to predict the boundary of white appearance and the degree of whiteness under each

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ambient lighting condition using the forced-choice and the magnitude estimation judgments made by the observers respectively. When the ambient lighting condition had chromaticities on the Planckian locus and CCT above 3000 K, the chromaticities of the whitest stimulus was also on the Planckian locus and both the whiteness boundary and the whitest stimulus shifted towards a higher CCT with the increase of the ambient lighting CCT. When the ambient lighting condition had chromaticities on the Planckian locus but CCT below 3000 K, the chromaticities of the whitest stimulus was slightly below the Planckian locus and the whiteness boundary also covered the larger area below the Planckian locus. When the ambient lighting condition had chromaticities off the Planckian locus, the chromaticities of the whitest stimulus was below the Planckian locus. For those with a same CCT but different D_{uv} values, both the whiteness boundary and the chromaticities of the whitest stimulus shifted in the same direction with the change of the lighting chromaticity.

The chromaticity difference between the whitest stimulus and the ambient lighting condition was speculated due to the incomplete chromatic adaptation, especially given the self-luminous stimuli provided by the tablet display. The degree of chromatic adaptation under each ambient lighting condition, in relative to that under the 6500 K lighting condition was optimized. Both the 4000 and 5000 K ambient lighting conditions were found to provide a similar degree of chromatic adaptation as the 6500 K lighting condition; while the conditions with a lower CCT provided a lower degree of chromatic adaptation, which corroborated the findings in a recent study [28]. For the lighting conditions with the chromaticities off the Planckian locus, a D_{uv} of −0.02 was found to provide a higher degree of chromatic adaptation than D_{uv} values of −0.04 and + 0.02. It is worthwhile to further expand the chromaticity regions of both ambient lighting conditions and the display stimuli to comprehensively investigate the degree of chromatic adaptation.

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