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Modelling incomplete chromatic adaptation on a display under different ambient illuminations

Rui Peng, Ming Ronnier Luo*, Mingkai Cao
State Key Laboratory of Modern Optical Instrumentation, Zhejiang University; Hangzhou, China
****m.r.luo@zju.edu.cn.***

Abstract

The purposes of this study was to investigate the chromatic adaptation and adaptive whites on a display under various ambient lighting conditions with different chromaticity and illuminance. An image including black text and white background was rendered by means of the CAT02 chromatic adaptation transform, into 42 different white stimuli varying at 6 CCTs and 7 Duv levels. Twenty observers assessed the neutral white evaluations of each color stimulus via psychophysical experiments. The optimization based on the neutral white stimulus under each ambient lighting condition suggested a lower degree of chromatic adaptation under the conditions with a lower CCT and a lower illuminance level. The results were used to model the adaptive display white and the incomplete adaptation factor (D) for CAT02 under different ambient illumiantions.

Introduction

Chromatic adaptation (CA) is the human visual system's ability to adjust to changes in illumination resulting in preserved appearance of object colors [1]. Chromatic adaptation transforms (CAT) are the models to predict these chromatic shifts, such as the most widely used CAT02 [2] in CIECAM02 [3] and the most recent CAT16 [4] in CIECAM16 [4], which are used to predict corresponding colors [5], two colors under two different illuminants to have same appearance. CAT02 includes an incomplete adaptation factor (D) varying from 0 (no adaptation) to 1 (full adaptation). A typical formula to calculate D values in the CAT02 transform were given by Eq. (1):

$$D_1 = F\left[1 - \left(\frac{1}{3.6}\right) e^{\left(\frac{-L_A - 42}{92}\right)}\right] \tag{1}$$

where L_A is the luminance (cd/m^2) of adapting field and F is a factor dependent on the surround conditions, where F=1 for 'average' surrounds while F=0.9 and F=0.8 for 'dim' and 'dark' ones.

In this equation, D is only affected by the luminance level regardless of the chromaticity of the illuminants, with a higher degree of chromatic adaptation under a higher adapting illuminance level [6]. However, several studies have found that D should be depending on not only illuminance but also the chromaticity of the illuminant [1, 7]. A lower degree of chromatic adaptation was found to happen under a lower adapting CCT condition [1, 8-11]. Wei and Chen [9, 10] conducted an experiment for adjusting stimulus with the whitest appearance on an iPad display under different adapting backgrounds. They found that the effects of adapting illuminance and CCT on the degree of chromatic adaptation are not isolated.

Models of effective degree of adaptation were proposed [7, 11-12]. Zhai and Luo [11] investigated the chromatic adaptation via neutral white matching using both surface and self-luminous colors and optimized D values of each corresponding colors pair to derive models of the effective degree of chromatic adaptation based on the chromaticities of illuminants. These are given in Eq. (2) and Eq. (3):

$$D_2 = 0.723 \cdot \left(1 - \frac{1116}{CCT} + 8.46 \cdot Duv - \frac{49266 \cdot Duv}{CCT}\right) \tag{2}$$

$$CCT > 2000K,\ Duv \in [-0.03, 0.03]$$

$$D_3 = 28u'^2 - 30.19v'^2 - 24.11u'v' - 1.78u' + 32.58v' - 6.52 \tag{3}$$

$$u' \in [0.15, 0.30],\ v' \in [0.40, 0.55]$$

where D_2 and D_3 were the modeled effective degree of adaptation with u' and v' as the CIE1976 chromaticity of the adapting illuminant. However, Eq. (2) and Eq. (3) are not universal model of effective D but only for the cases of self-luminous display with ambient adapting illuminants around the blackbody locus. An offset or a scaling factor of D values might be added in the equations according to different luminance level. Further, the CCT and luminance levels of the adapting field jointly affected the degree of chromatic adaptation, which needs to be modelled together for color appearance models and uniform color spaces.

In this study, a psychophysical experiment was carried out to evaluate neutral white color stimuli on a display under various ambient lighting conditions with different adapting illuminance and CCT levels. The study is aimed to investigate the effect of color and illuminance of ambient illumination on chromatic adaptation for display, and propose an incomplete adaptation model based on the chromaticities and illuminance level of illuminants. Note that for a lambertian body luminance level in cd/m^2 equals to illuminance times π.

Experimental

Stimuli

An image composed of white background and black text was selected in the experiment, with dimensions of 15 cm × 26.4 cm. Black frame was added for simulate mobile device, the width is about 10% of the original image. The original image under D65/10 was converted by means of a chromatic adaptation transform (CAT02) [2], into 42 different white points varying at 6 CCTs (3000, 4000, 5000, 6500, 8000 and 10000 K) and 7 D_{uv} levels (-0.015, -0.010, -0.005, 0, 0.005, 0.010, 0.015). Figure 1 shows the chromaticity coordinates of 42 white points in CIE 1976 $u'v'$ chromaticity. A 30-inch NEC PA302W display, with resolution of 2560 × 1600 pixels was used to stimulus presentation. The transformed image was presented on the center of the display, as shown in Figure 2. Observers only viewed the image and border, the rest was covered by a mid-grey cardboard having L* of 63.

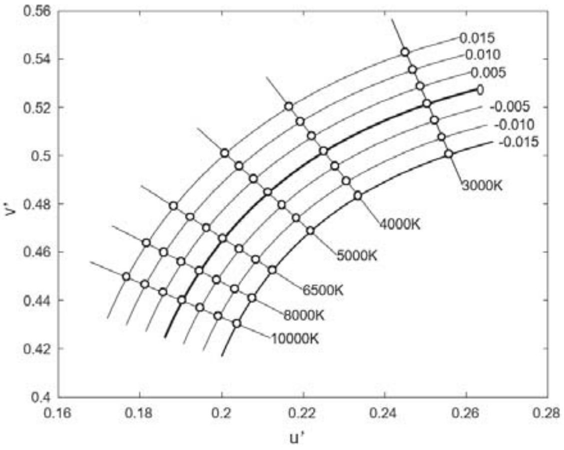

Figure 1. The 42 white points at 6 different CCTs and at 7 different Duv levels in CIE 1976 u'v' chromaticity diagram.

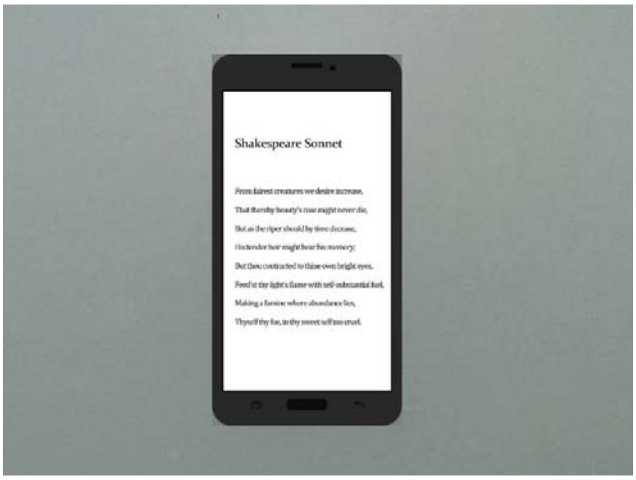

Figure 2. An image composed of white background and black texts was displayed on the center of a desktop display.

Ambient illuminants

A spectrum tunable LED illumination system, LEDCube from Thouslite® was used to produce different lighting conditions. It includes twelve identical light units that are evenly arranged on the ceiling, and semi-transparent frosted diffuser plates are installed to ensure uniform and stable light emission. There were ten ambient lighting conditions, including two illuminance levels (500 and 1000 lx) and five CCTs (3000, 4000, 5000, 6000 and 8000 K) with chromaticities on the Planckian locus. The ambient illuminants were characterized using a calibrated JETI-Specbos 1211 tele-spectroradiometer. Table 1 summarizes the colorimetric characteristics of all the 10 ambient illuminants. The average luminance of display under different ambient lighting conditions was around 100 cd/m^2.

Figure 3 shows the experimental situation. The experiment was carried out in a room with no window to eliminate the effects of natural light, and it was arranged like an office. Walls and ceilings are white or wood, and most of the furniture is black, reducing the interference of other color stimuli to the observer. In order to illuminate the display screen and simulate the typical mobile phone application, the display was placed at a 45° angle below the center of the light source. A chair was set in front of the display with a distance around 75 cm. The height of the chair was adjustable to ensure that each observer could have a viewing geometry of 45^o/0^o to avoid the glare from the screen.

Table 1. Colorimetric characteristics of the 10 ambient illuminants.

Nominal CCT(K)	CCT (K)	D_{uv}	CIE 1976 (u',v')	Lx	R_a
3000	3008	+ 0.0001	(0.2503, 0.5214)	506	93
4000	4007	+ 0.0004	(0.2248, 0.5019)	505	94
5000	5023	- 0.0001	(0.2112, 0.4842)	501	99
6000	6039	+ 0.0001	(0.2030, 0.4709)	502	97
8000	8024	- 0.0001	(0.1946, 0.4519)	500	98
3000	2980	- 0.0004	(0.2515, 0.5212)	1006	93
4000	3998	- 0.0024	(0.2265, 0.4986)	1002	96
5000	5007	+ 0.0002	(0.2112, 0.4848)	1005	99
6000	6023	+ 0.0025	(0.2012, 0.4733)	1001	98
8000	7956	+ 0.0017	(0.1933, 0.4537)	1004	98

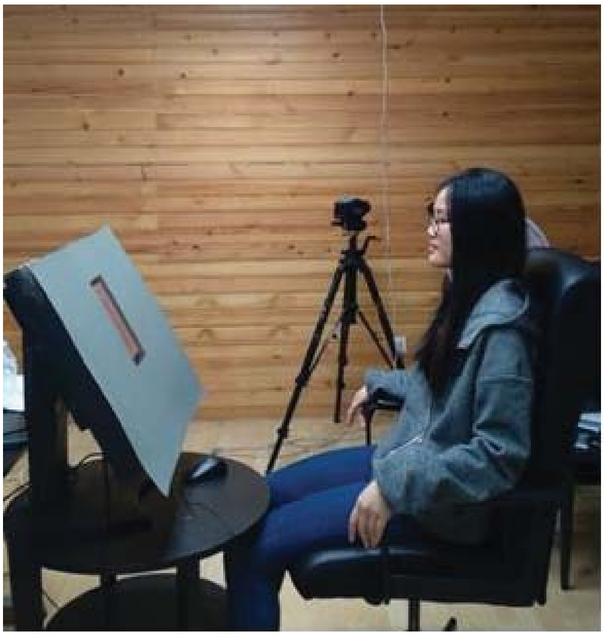

Figure 3. Experimental situation.

Observers and procedure

In total, 20 observers participated in the experiment, including 10 males and 10 females. Their ages were between 20 and 24 years old (mean = 22.4, std. dev. = 1.84). All observers passed the Ishihara color vision test and had normal color vision. The observers were divided into two groups (10 observers each), low adapting illuminance (500 lx) and high adapting illuminance (1000 lx). Each observer was required to evaluate 48 color stimuli (42 display stimuli + 6 repeated stimuli on the Planckian locus for evaluating intra-observer variation) under five ambient illuminants and one dark condition. They were asked to make a forced choice to judge whether the color of the stimulus can be classified as 'white' or 'not a white'.

There was a training session before the formal experiment for each observer to evaluate five stimuli in the specified ambient lighting condition to familiarize with the experiment procedure. When the ambient illuminant changed, the observer was asked to close her or his eyes. After that, the observers opened their eyes to adapt in the environment for one minute. Each stimulus was presented for 5 seconds and the observer was required to orally report the judgement. The same procedure was repeated for all the 48 stimuli under each ambient lighting condition. The orders of stimuli and ambient illuminants for each observer were randomized to avoid any sequential effect.

Results and discussions

Inter- and intra-observer variations

The intra- and inter-observer variations were quantified using the Standardized Residual Sum of Squares (*STRESS*) [13], which has been widely used in color appearance evaluations. A larger *STRESS* means a larger disagreement. A *STRESS* of 0 and 20 means perfect agreement and 20% variation between two sets of data respectively.

The inter-observer variation was calculated between the individual results and the mean results rated by all observers under each ambient lighting condition. Table 2 summarizes the *STRESS* values of the 10 ambient lighting conditions, ranged between 18 and 32, which was quite typical compared with another study [8].

Each observer evaluated 6 identical stimuli twice under each ambient lighting condition. The intra-observer variation was computed by comparing the repeated evaluations under each ambient lighting condition for each observer. Table 3 lists the *STRESS* values of the 10 ambient lighting conditions, ranged between 9 and 18, which was again typical compared with another study [8].

Table 2. Inter-observer variations in terms of *STRESS* unit.

CCT(K)\ Lx	3000	4000	5000	6000	8000	mean
500	32	24	26	28	31	28
1000	23	32	27	27	18	25

Table 3. Intra-observer variations in terms of *STRESS* unit.

CCT(K)\ Lx	3000	4000	5000	6000	8000	mean
500	9	9	13	16	15	12
1000	13	17	18	17	18	16

Neutral white under each adapting condition

Figure 4 shows the corresponding CCT and D_{uv} of adaptive neutral white rated by observers under each ambient lighting condition. Figure 4(a) shows that neutral white shifted towards a higher CCT with an increase of the ambient lighting CCT and Figure 4(b) shows that D_{uv} was always located on or slightly above the Planckian locus. The chromaticty of the neutral white stimuli under different ambient lighting conditions in CIE 1976 $u'v'$ chromaticity diagram are shown in Figure 5. The vectors in the chromaticity diagram represent the neutral white shift under each illuminant from the full adaptation prediction (chromaticity same as the illuminant) to the visual results. The filled black circle represents the neutral white stimuli rated by observers under dark-adapted condition.

The neutral whites under low CCT illuminants (3000~6000 K) shifted to the direction of higher CCT away from the chromaticity of the ambient illuminants, while results under high CCT (8000 K) shifted towards lower CCT. The present results clearly indicate that the adapted neutral white of display had a large shift according to the ambient illuminants, suggesting a great incomplete chromatic adaptation under these ambient lighting conditions. The lower the CCT of the ambient illuminants, the larger the chromaticity shifts. Note that for a more complete adaptation, the shift should be small.

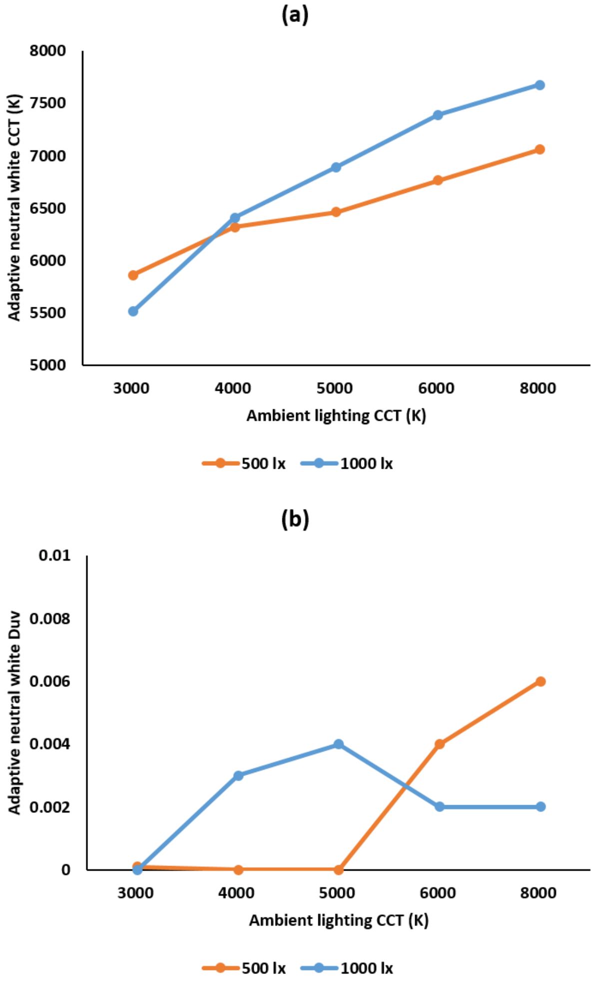

Figure 4. The corresponding a) CCT and b) D_{uv} of adaptive neutral white rated by observers under each ambient lighting.

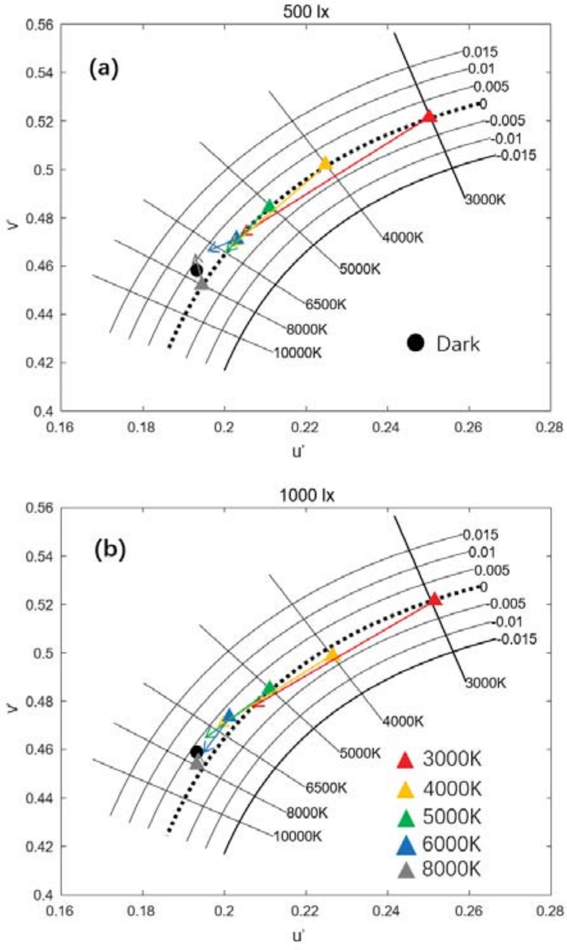

Figure 5. The neutral white shift from the adapting chromaticities to the visual results under each adapting condition in CIE 1976 u' v' chromaticity diagram. (a) Low LA (500 lx); (b) High LA (1000 lx).

Degree of chromatic adaptation

The 6000 K ambient lighting condition was selected as 'neutral white' for investigating the degree of chromatic adaptation under other lighting conditions according to Smet *et al's* neutrality for object illumination [14]. CAT02 was used to transform the neutral white results under each ambient lighting condition (3000, 4000, 5000 and 8000 K) to the corresponding chromaticities under the 6000 K condition. The degree of chromatic adaptation *D* under each ambient lighting condition was optimized by minimizing the color difference ΔE_{00} [15] between the transformed chromaticity and the neutral white rated under the 6000 K condition. Note that 6000K was found by Smet et al as the most neutral colour for object mode colours [14]. The optimized *D* values, in relative to that under the 6000 K, are shown in Figure 6. The trend of these optimized *D* factors was similar to that found by Zhai and Luo [12]. Note that a smaller *D* value means a more incomplete chromatic adaption. It was found that the adapting CCT and luminance levels jointly affect the degree of chromatic adaptation, with a higher CCT and a higher adapting luminance level introducing a more complete chromatic adaptation.

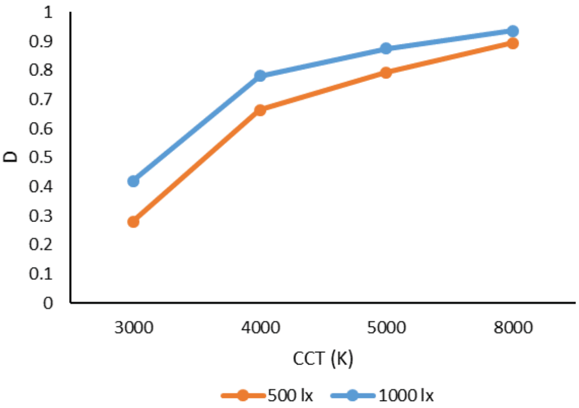

Figure 6. The optimized degree of chromatic adaptation D under each ambient lighting condition.

Models of imcomplete adaptation factor (D)

Based on the optimized *D* values, the effective degree of adaptation for display were modeled as as Eq. (4) and Eq. (5) for CAT02:

$$D_4 = a_1 \cdot \left(1 - \frac{a_2}{CCT} + a_3 \cdot Duv - \frac{a_4 \cdot Duv}{CCT}\right) \cdot \ln L \qquad (4)$$

$$D_5 = \left(a_1 u^2 + a_2 u'v' + a_3 v'^2 + a_4 u' + a_5 v' + a_6\right) \cdot \ln L \qquad (5)$$

where a_1 to a_6 are the optimized model parameters; *L*, *u'* and *v'* as the luminance level (lx) and the CIE1976 chromaticities of the adapting illuminants respectively. The equation structure is based on the incomplete adaptation model developed by Zhai and Luo [11]. Using the optimized *D* values discussed earlier as modelling input, the fitting parameters and the Pearson correlation coefficient between the optimized *D* values and the modelled *D* values are given in Table 5. Figure 7 shows the optimized *D* values and the modelled *D* values. The average *r* value between models and the training samples is 0.976, suggesting that the effective degree of adaptation for display were accurately modeled.

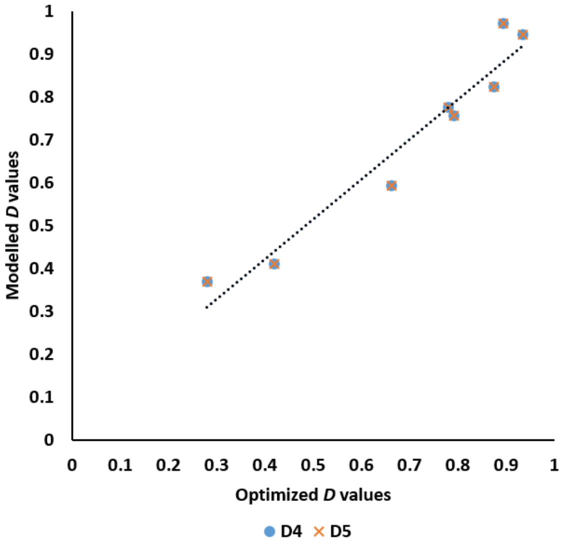

Figure 7. Correlation between the optimized D values and the modelled D values.

Table 5. Fitting parameters and the Pearson correlation coefficient between the optimized D values and the modelled D values.

Model	*a*$_1$	*a*$_2$	*a*$_3$	*a*$_4$	*r*
D$_4$	0.21	2165.79	70.44	-165338	0.97
D$_5$	-160.63	238.93	-375.44	-31.47	0.98
	a$_5$	*a*$_6$			
	293.30	-63.76			

The errors of CAT02 with *D* values from the above models are listed in Table 6 in comparison with D_1 in Eq. (1), D_2 in Eq. (2), D_3 in Eq. (3) and *D* = 1. The accuracy of the above models (Eq. (1-5)) for self-luminous neutral white were higher than *D* = 1, which proved the jointly effect of the adapting illuminant's chromaticity and luminance level on degree of adaptation. The mean error of new incomplete adaptation models is 3.2 CIEDE2000c units markedly better than those with *D* =1 (11.4 units) and with *D* in other models.

Table 6. The errors of CAT02 with different D values in terms of CIEDE2000 without lightness differences

CCT (K)	With *D* = 1	with D_1	with D_2	with D_3	with D_4	with D_5
3000	19.14	17.27	9.45	8.66	5.01	5.00
4000	14.33	12.75	6.04	6.04	3.52	3.64
5000	6.82	5.83	3.23	3.36	3.53	2.76
8000	5.15	3.62	1.66	1.74	0.99	1.18
Mean	11.36	9.87	5.10	4.95	3.26	3.15

The chromaticities of the rated neutral white stimuli were also calculated in CAM16-UCS, as shown in Figure 8, with the degree of chromatic adaptation factor *D* being set to 1 and modelled values based on D_4 respectively. The vectors in the diagram represent the neutral white shift under each illuminant from *D* = 1 (most incomplete adaptation) to D_4 (relatively better adaptation). The average chromaticity difference between the rated neutral white stimuli and the origin in CAM16-UCS *a*' -*b*' plane is shown in Figure 9.

The chromaticity differences under different ambient lighting conditions suggested a higher degree of chromatic adaptation under a higher CCT and a higher luminance level, which was consistent to the findings in many recent studies [9-11]. However, under higher adapting CCT (6000 and 8000 K), the difference between two luminance levels became less obvious. The model performed markedly better for lower adapting CCT (especially for 3000 and 4000 K). However, the study was only carried out under two adapting luminance levels and with ambient adapting illuminants on the Planckian locus. Future works are needed to test the results on display under ambient illuminants with a wider range of chromaticity and luminance level.

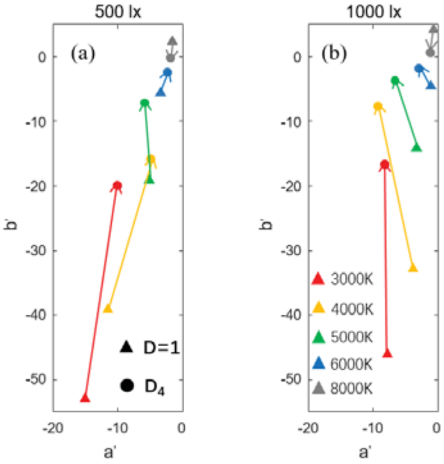

Figure 8. *The chromaticities of the rated neutral white stimuli under each adapting condition in a'-b' plane of CAM16-UCS. (a) Low L_A (500 lx); (b) High L_A (1000 lx).*

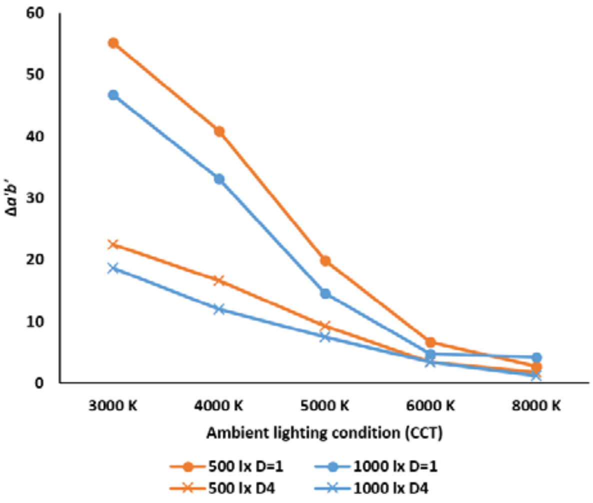

Figure 9. *Chromaticity differences between the chromaticities of the neutral white stimuli rated by the observers and the origin in CAM16-UCS a'-b' plane under each adapting condition.*

Conclusions

A psychophysical experiment was conducted to investigate the effects of chromaticity and luminance of ambient illuminat on chromatic adaptation for a display. Observers were asked to evaluate the neutral white perception of 42 stimuli under different ambient lighting conditions. The results were used to obtain an effective degree of adaptation of CAT02, *D*, by minimizing the color difference under each illuminant condition. The results indicated that chromatic adaptation is highly affected by the ambient CCT and luminance levels. In general, lower adapting CCT and lower adapting luminance give less complete adaptation on display. The results were used to investigate possible ways forward for extending or adjusting the formula for the degree of adaptation in CAT02 for adapting fields with varying CCT and illuminance. Two types of model for the *D* factor in CAT02 were developed, one as a function of CCT, D_{uv} and illuminance, and one as a function of the $u'v'$ chromaticity and illuminance of ambient illuminat. However, further study is required to verify these new D functions.

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Author Biography

Rui Peng received her BSc degree in Printing Engineering from Wuhan University (2018) and has been a Master student supervised by Professor Ming Ronnier Luo at Zhejiang University since 2018. Her work is focused on color appearance.