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Effects of adapting luminance and CCT on appearance of white and degree of chromatic adaptation

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Abstract: Past studies reported that the degree of chromatic adaptation was affected by viewing medium and adapting luminance. In this study, human observers adjusted the color appearance of a stimulus produced by a self-luminous display to make it appear as white as possible under different adapting conditions, whose adapting luminance and Correlated Color Temperature (CCT) levels were systematically varied. Though an identical display was used as the viewing medium, the chromaticities adjusted under the high adapting luminance levels were generally around the adapting chromaticities, which was similar to the findings in the past studies using reflective surface color samples as the viewing medium. This suggested that the effect of the viewing medium, as reported in the past studies, was actually the effect of viewing mode, due to the change in adapting luminance. Furthermore, the adapting luminance and CCT were found to jointly affect the degree of chromatic adaptation, with a stronger effect of adapting luminance under a lower adapting CCT.

1. Introduction

Chromatic adaptation, an important mechanism in the human visual system, helps to approximately preserve the color appearance of illuminated objects by automatically removing the color cast of the illumination. For example, a piece of white paper remains to appear white, regardless whether it is viewed under a bluish daylight or yellowish incandescent lamp. Chromatic adaptation involves both sensory and cognitive mechanisms. The former refers to the automatic changes caused by stimuli, including the sensitivity controls in the photoreceptors and neurons; the latter refers to the changes that happen based on observers' knowledge of stimuli and viewing conditions [1].

Many studies have been carried out to develop models to predict this important mechanism, so that the color appearance of objects or images can be faithfully reproduced under different lighting and viewing conditions. The adapting luminance level has been found to significantly affect the degree of chromatic adaptation, with a higher degree of chromatic adaptation under a higher adapting luminance level [1]. For example, the most widely used chromatic adaptation transforms (CAT)—CAT02—and its revised version—CAT16—characterize the degree of chromatic adaptation using Eq. (1) [2–4].

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

where:

D: the degree of chromatic adaptation factor (between 0 and 1);

F: a surround parameter, with 1.0 for an average surround, 0.9 for a dim surround, and 0.8 for a dark surround;

L_A: the adapting luminance level.

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Recently, several studies found that the effect of the chromaticities of the adapting field on the degree of chromatic adaptation cannot be ignored. A lower degree of chromatic adaptation was found to happen under a lower adapting CCT [5–11]. These studies, however, were only carried out under a single adapting luminance level, which failed to reveal whether the effects of adapting luminance and adapting CCT were isolated.

Furthermore, many studies argued that viewing medium also significantly affected the degree of chromatic adaptation. In these studies, human observers were asked to adjust stimuli, which were produced using either self-luminous displays or reflective surface color samples (e.g., Munsell color samples), to make them appear the whitest under different adapting conditions. It was found that the chromaticities for producing the whitest appearance were significantly different for these two viewing media. When using self-luminous displays, the chromaticities for producing white appearance were found to be shifted along the Planckian locus towards a higher CCT [5,10,12–17]; when using reflective surface colors samples, the chromaticities for producing white appearance were found much closer to the chromaticities of the adapting conditions [7–10]. Such a difference has been commonly attributed to the different degrees of chromatic adaptation caused by the two viewing media. When viewing reflective surface color samples, a higher degree of chromatic adaptation was thought to happen, with both sensory and cognitive mechanisms being active, since the cognitive mechanisms would respond to the prevailing illumination to discount its color cast. When viewing self-luminous displays, a lower degree of chromatic adaptation was thought to happen, with only sensory mechanisms being active [1]. However, viewing medium (i.e., self-luminous displays or reflective surface color samples) and viewing mode (i.e., self-luminous mode or surface mode) [1], were generally confounded in these studies, though they are actually independent to each other. A same viewing medium can be viewed in different viewing modes due to the change of luminance contrasts between the stimulus and the background [18–20]. For example, a self-luminous stimulus can be viewed in the surface mode [18–20], while a surface color can be viewed in the self-luminous mode (e.g., fluorescence samples). Therefore, it is likely that the chromaticity difference for producing white appearance was actually caused by the viewing mode instead of the viewing medium.

In this study, human observers were asked to adjust the color appearance of a stimulus produced by a self-luminous display under various adapting conditions with different adapting luminance and CCT levels. Specifically, the adapting luminance levels covered a wide range for allowing the identical viewing medium (i.e., the self-luminous display) to be viewed in two different viewing modes (i.e., self-luminous and surface modes), so that the effects of viewing mode and viewing medium can be isolated. We hypothesized that (1) The different chromaticities for producing white appearance using self-luminous displays and reflective surface color samples were caused by the different viewing modes instead of the different viewing media; (2) The effects of adapting luminance and CCT on the degree of chromatic adaptation are not isolated.

2. Methods

2.1 Apparatus, adapting conditions, and stimuli

The experiment was carried out using a viewing booth, with dimensions of 60 cm (width) × 60 cm (depth) × 60 cm (height). Munsell N7 spectrally neutral paint was used to paint the interiors of the booth. A spectrally tunable LED device, which was placed above the viewing booth to provide a uniform illumination, was used to produce different adapting conditions. A 45° viewing table was placed at the center of the viewing booth. An iPad Air 2, with the display being covered by a Munsell N7 sheet (i.e.,S0530-Y90R, S1040-R80B, S0580-Y90R, S0550-Y50R, S0550-Y10R, S4040-Y30R, S1030-G, S0540-R30B), was placed on the viewing table. A 3 cm × 3 cm opening was cut at the center of the Munsell sheet, so that the area being viewed through the opening was employed as the color stimulus. A chromatic background, which was created by attaching eight 3 cm × 3 cm Natural Color System (NCS)

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color samples around the center opening, were used to help chromatic adaptation. During the experiment, the observers viewed the color stimulus produced by the iPad through the opening by keeping their chins on a chin-rest, which was mounted just outside the viewing booth, so that the stimulus was viewed perpendicularly with a field of view (FOV) around 4°. The experiment setup is shown in Fig. 1.

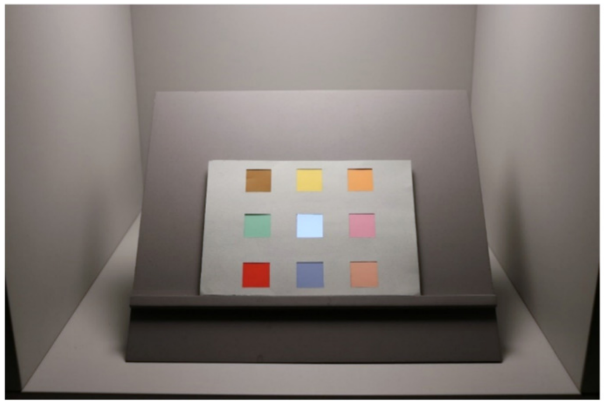

Fig. 1. Photograph of the experiment setup. The color stimulus at the center was produced by an iPad display, which was placed behind the Munsell sheet and viewed through the 3 cm × 3 cm opening on the sheet. The eight surrounding colors were Natural Color System (NCS) color samples, which were used to produce a chromatic background for chromatic adaptation.

Table 1. Colorimetric characteristics of the adapting conditions.

Nominal L_w (cd/m^2)	Nominal CCT (K)	CIE 1976 (u'_{10},v'_{10})	CCT (K)	D_{uv}	L_w(cd/m^2)	CRI R_a	IES TM-30-15 R_f
115	2700	(0.267,0.525)	2704	−0.0012	115.9	97.3	93.7
	3500	(0.236,0.516)	3516	+0.0030	116.1	97.9	92.5
	5000	(0.208,0.493)	4997	+0.0080	117.3	96.8	96.4
	6500	(0.196,0.471)	6514	+0.0054	116.7	97.4	97.4
300	2700	(0.269,0.526)	2679	−0.0009	300.0	94.8	89.7
	3500	(0.240,0.508)	3498	−0.0030	299.0	88.4	88.9
	5000	(0.215,0.484)	4993	−0.0020	302.0	93.9	89.8
	6500	(0.204,0.466)	6482	−0.0016	301.0	94.2	88.2
600	2700	(0.268,0.526)	2693	−0.0004	599.5	94.6	89.7
	3500	(0.240,0.511)	3477	−0.0004	604.0	90.0	89.5
	5000	(0.216,0.482)	4994	−0.0028	610.0	94.2	89.8
	6500	(0.202,0.468)	6491	+0.0008	609.5	94.3	88.6
900	2700	(0.269,0.529)	2670	+0.0009	900.1	94.5	90.2
	3500	(0.240,0.511)	3485	−0.0008	911.6	90.1	89.7
	5000	(0.215,0.482)	5042	−0.0024	907.7	93.6	89.8
	6500	(0.204,0.466)	6501	−0.0015	908.0	94.2	88.0
	8000	(0.197,0.453)	8018	−0.0018	910.3	94.1	87.2

The iPad display was calibrated using a gamma-offset-gain (GOG) display model [21] and the CIE 1964 10° Color Matching Functions (CMFs). A customized program was then developed based on the GOG model, so that the four arrow keys on a Bluetooth keyboard can remotely adjust the chromaticities of the display along the u'_{10} and v'_{10} axes in the CIE 1976 $u'_{10}v'_{10}$ chromaticity diagram, with a step of 0.001 unit, at a constant luminance level. In the experiment, the display was calibrated to produce stimuli at six different luminance levels (i.e., 100, 150, 200, 250, 300, and 350 cd/m^2). The gamut of the display at each of these six

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luminance levels was verified to cover the chromaticities of the blackbody radiators between 2700 and 6500 K, which was the CCT range of the adapting conditions.

Seventeen adapting conditions were created using the LED device. Sixteen conditions were organized as a 4 × 4 factorial design, comprising four levels of CCT (i.e., 2700, 3500, 5000, and 6500 K) and four levels of adapting luminance (i.e., $L_w \approx 115$, 300, 600, and 900 cd/m^2); an additional adapting condition with a CCT of 8000 K was also created for the L_w of 900 cd/m^2. The intensities of the LED channels in the LED device were carefully designed and adjusted, so that the CIE General Color Rendering Index (CRI R_a) of all the adapting conditions were generally above 90. The adapting conditions were calibrated using a calibrated JETI Specbos 1411UV spectroradiometer and a calibrated Labsphere reflectance standard being placed at the center of the viewing table. Table 1 lists the colorimetric characteristics of all the 17 adapting conditions.

2.2 Observer

Eight observers (seven males and one female) completed the experiments. The observers were between 22 and 28 years of age (mean = 24.3, std. dev. = 2.3) and had a normal color vision, as tested using the Ishihara Color Vision Test. All experimental procedures were in agreement with the Helsinki declaration and approved by the Hong Kong Polytechnic University's Institutional Review Board.

2.3 Experimental procedure

Upon arrival, the experimenter explained the procedure and task of this experiment to the observer and the observer completed the Ishihara Color Vision Test. Then the observer was escorted to the viewing booth, with his or her chin being fixed on the chin rest. Under each adapting condition, the observer was asked to look into the booth for two minutes, which could achieve more than 90% adaptation [22–24]. The experimenter then placed the iPad, which was being covered with the Munsell sheet and the eight NCS samples, on the center of the viewing table. The iPad has been switched on for 30 minutes before the experiment for stabilization. The luminance of the display was set to one of the six levels, with the chromaticities being randomly selected. The observer then adjusted the color appearance of the stimulus (i.e., the small area of the display that was viewed through the center of the Munsell sheet) using the four arrow keys on a Bluetooth keyboard, so that the stimulus appeared the whitest to him or her. The four keys adjusted the chromaticities of the display along the u'_{10} and v'_{10} axes in the CIE 1976 $u'_{10}v'_{10}$ chromaticity diagram, with a step of 0.001 unit, at a constant luminance level. After the observer completed the adjustment, the experimenter helped him or her to verify the decision by making an additional one-step adjustment along the four directions (i.e., $+u'_{10}$, $-u'_{10}$, $+v'_{10}$, and $-v'_{10}$). The same procedure was repeated for all the six stimulus luminance levels and all the adapting conditions. The orders of the stimulus luminance levels and adapting conditions were randomized.

3. Results

After the observers completed the experiment, the spectral power distribution (SPD) of each adjusted stimulus was measured under the corresponding adapting condition using the calibrated JETI specbos 1411UV spectroradiometer, which considered the light emitted by the display and the light reflected by the display. The measured SPDs were then used to derive various colorimetric quantities in the following analyses.

The measured luminance level of the adjusted stimulus was 5.8% to 1.6% (mean = 4.38%, std. dev. = 0.073) lower than the calibrated luminance level; the adjusted stimuli were always far from the display gamut at the corresponding display luminance.

3.1 Inter-observer variations

The inter-observer variations were characterized based on the adjustments made by each observer and an average observer under each adapting condition using the mean color using the mean color difference from the mean (MCDM) in the CIE 1976 $u'_{10}v'_{10}$ chromaticity diagram, as summarized in Table 2.

Table 2. Inter-observer variations, in terms of the mean color difference from the mean (MCDM) in the CIE 1976 $u'_{10}v'_{10}$ chromaticity diagram, under each adapting condition.

	L_w = 115 cd/m^2	L_w = 300 cd/m^2	L_w = 600 cd/m^2	L_w = 900 cd/m^2
2700K	0.0091	0.0196	0.0114	0.0102
3500K	0.0088	0.0115	0.0102	0.0080
5000K	0.0084	0.0088	0.0089	0.0063
6500K	0.0079	0.0083	0.0087	0.0056
8000K	-	-	-	0.0060

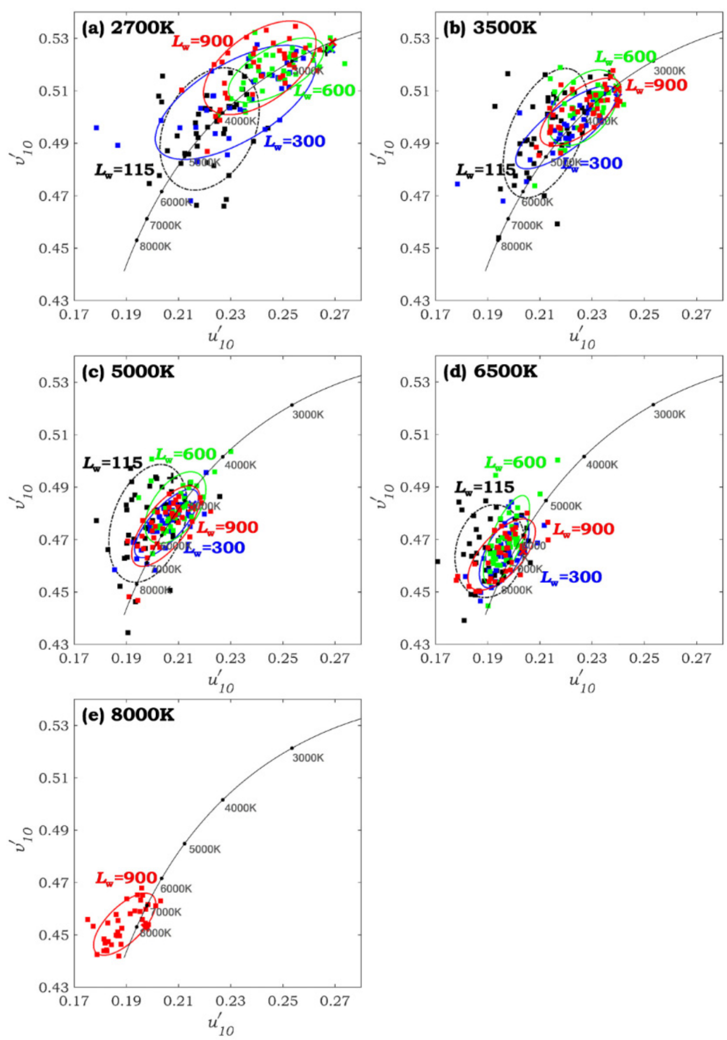

Fig. 2. Chromaticities of all the adjustments, together with the 95% confidence error ellipses, made by the observers under the four adapting luminance levels and each adapting CCT in the CIE 1976 $u'_{10}v'_{10}$ chromaticity diagram. (a) 2700K; (b) 3500K; (c) 5000K; (d) 6500K; (e) 8000K.

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In addition, the 95% confidence error ellipses of all the adjustments made by the observers under different adapting conditions are shown in Fig. 2. Both the MCDM values and the sizes of the ellipses were comparable to those in the several recent studies investigating white appearance and memory colors [10,11,25,26].

3.2 Average adjusted chromaticities under each adapting condition

The average chromaticities of the stimuli at different luminance levels adjusted by the observers under each adapting condition in the CIE 1976 $u'_{10}v'_{10}$ chromaticity diagram are shown in Fig. 3, with the average chromaticity difference between the adjusted stimuli and the adapting conditions, together with the 95% confidence interval, being shown in Fig. 4. It can be observed that the chromaticities of the adjusted stimuli were generally located around the Planckian locus. When the adapting conditions had an L_w of 115 cd/m^2, the chromaticities of the adjusted stimuli generally shifted towards the direction of a higher CCT along the Planckian locus and above the Planckian locus. Under the adapting conditions at 6500 K, the effect of adapting luminance appeared very small. Under the adapting conditions at 2700 and 3500 K, the increase of L_w made the chromaticities of the adjusted stimuli at different luminance levels much closer to each other and also much closer to the adapting chromaticities.

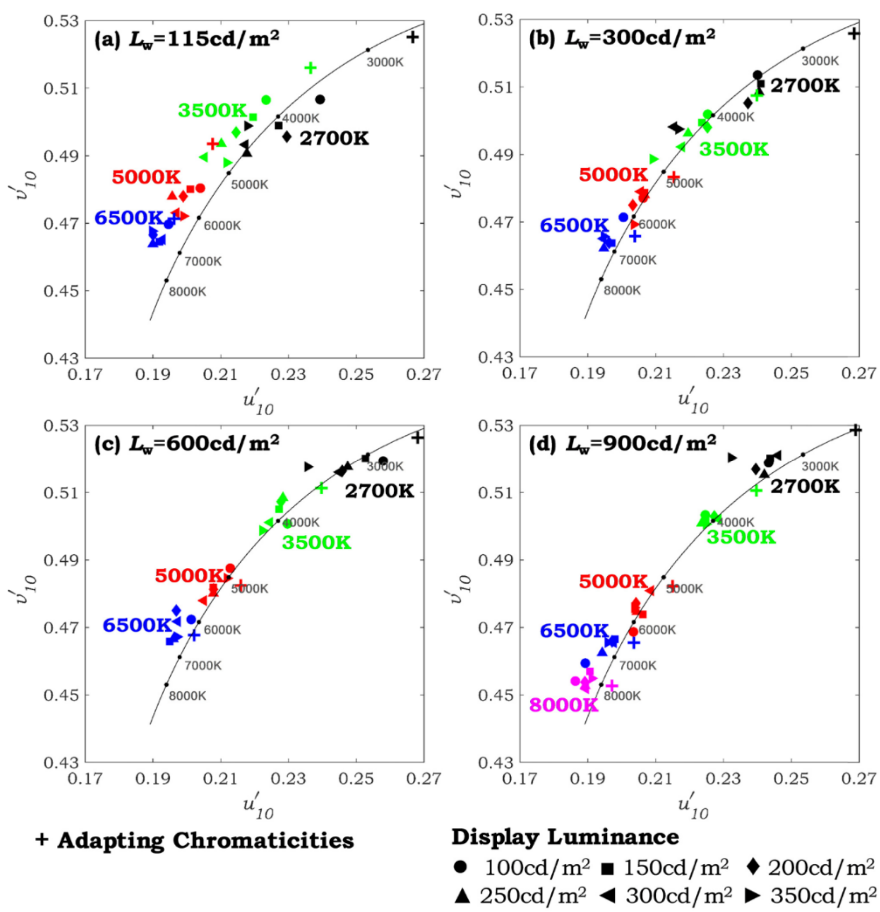

Fig. 3. Average chromaticities of the stimuli adjusted by the observers at each display luminance level under each adapting condition in the CIE 1976 $u'_{10}v'_{10}$ chromaticity diagram. (a) L_w = 115 cd/m^2; (b) L_w = 300 cd/m^2; (c) L_w = 600 cd/m^2; (d) L_w = 900 cd/m^2.

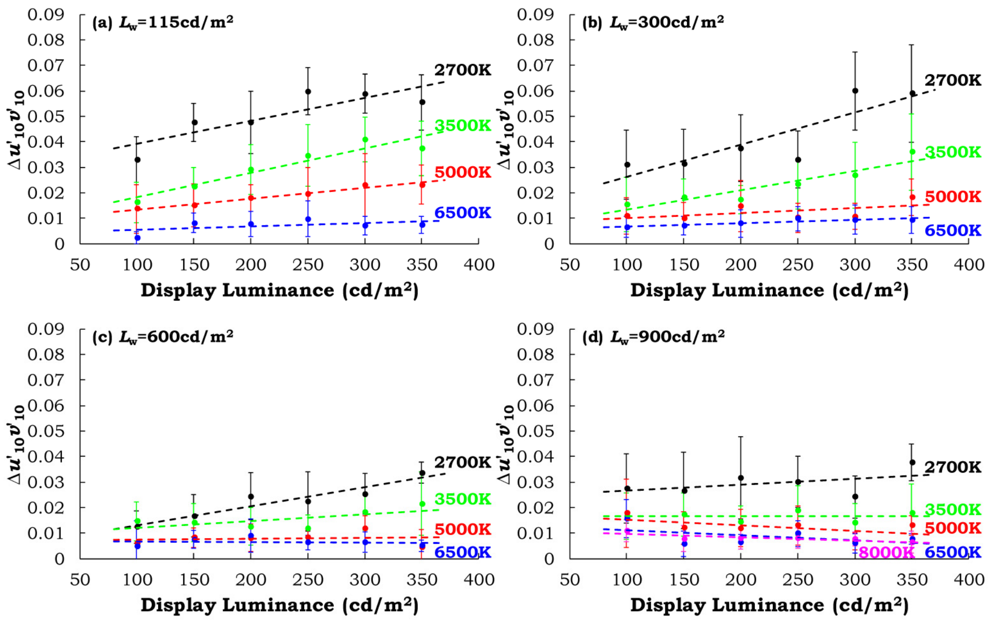

Fig. 4. Chromaticity differences, together with the 95% confidence interval, between the average chromaticities of the stimuli adjusted by the observers and the chromaticities of the adapting fields under each adapting condition in the CIE 1976 $u'_{10}v'_{10}$ chromaticity diagram. (a) L_w = 115 cd/m^2; (b) L_w = 300 cd/m^2; (c) L_w = 600 cd/m^2; (d) L_w = 900 cd/m^2.

The average chromaticities of the adjusted stimuli were also calculated in CAM02-UCS, as shown in Fig. 5, with the degree of chromatic adaptation factor D being set to 1. CAM02-UCS embeds a chromatic adaptation transform—CAT02—and also converts the stimulus luminance to lightness J', so that the effects of adapting luminance and chromaticities are considered. The average chromaticity difference between the adjusted stimuli and the origin in the a'_{10}-b'_{10} plane of CAM02-UCS, together with the 95% confidence interval, are shown in Fig. 6.

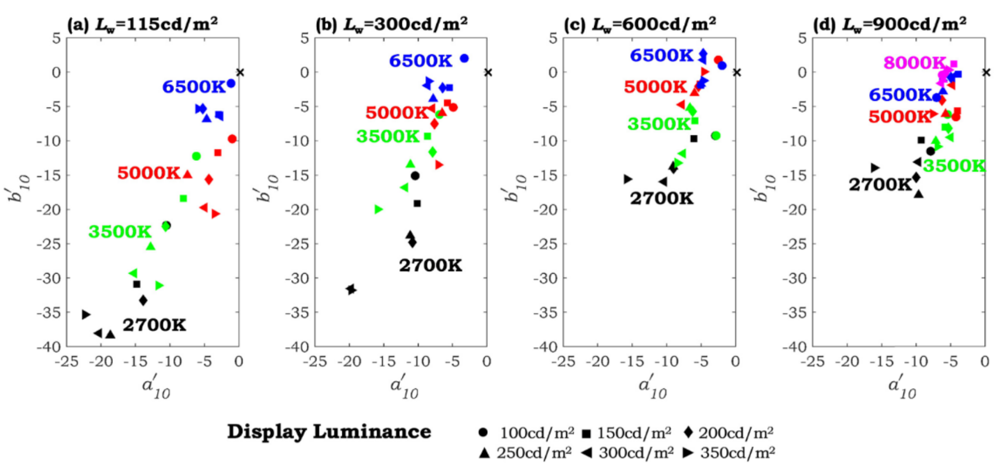

Fig. 5. Average chromaticities of the stimuli adjusted by the observers at each display luminance level under each adapting condition in the a'_{10}-b'_{10} plane of CAM02-UCS. (a) L_w = 115 cd/m^2; (b) L_w = 300 cd/m^2; (c) L_w = 600 cd/m^2; (d) L_w = 900 cd/m^2.

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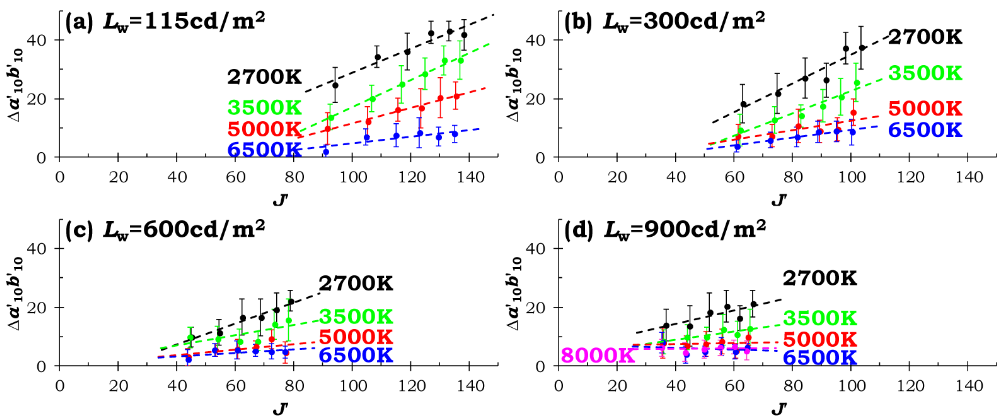

Fig. 6. Chromaticity differences, together with the 95% confidence interval, between the average chromaticities of the stimuli adjusted by the observers and the origin in the a'_{10}-b'_{10} plane of CAM02-UCS. (a) L_w = 115 cd/m^2; (b) L_w = 300 cd/m^2; (c) L_w = 600 cd/m^2; (d) L_w = 900 cd/m^2.

4. Discussions

4.1 Effect of adapting luminance on viewing mode

Though a same viewing medium (i.e., a self-luminous display) was used in this study and all the observers were well aware of the fact that they were adjusting the color appearance of a stimulus produced by a display, the results at the two adapting luminance levels (i.e. L_w of 115 and 900 cd/m^2) were similar to those in the past studies using two different viewing media. Specifically, the results under the adapting conditions with an L_w of 115 cd/m^2, as shown in Fig. 3(a), were very similar to those in the past studies using self-luminous displays [5,10,12–17,21], while the results under the adapting conditions with an L_w of 900 cd/m^2, as shown in Fig. 3(d), were very similar to those in the past studies using reflective surface color samples (e.g., Munsell samples or NCS samples) [8–10]. Therefore, the results in this study do not support the conclusion in many past studies that the necessity to have different chromaticities for producing white appearance using reflective surface color samples and self-luminous displays was due to the different viewing media.

Due to the change of the adapting luminance level, the six display luminance levels had different lightness levels. As shown in Fig. 6(a), when the adapting conditions had an L_w of 115 cd/m^2, five of the six display luminance levels had J' values greater than 100, since they were higher than L_w (i.e., the luminance of a perfect white under the same adapting luminance), which was likely to make the self-luminous stimuli appear self-luminous. When the adapting conditions had an L_w of 900 cd/m^2, all the six display luminance levels had J' values between 30 and 70, which was likely to make the self-luminous stimuli appear reflective as surface color samples. Thus, the findings in many past studies that self-luminous displays and surface color samples needed different chromaticities to produce white appearance were likely due to the different viewing modes (i.e., self-luminous mode versus surface mode) instead of the different viewing media (i.e., self-luminous displays versus reflective surface color samples).

When the adapting conditions had an L_w of 300 cd/m^2, though all the stimuli were expected to be viewed in the surface mode due to the fact that their J' values were around or below 100, the chromaticities of the two display luminance levels (i.e., 300 and 350 cd/m^2) under the conditions at 2700 K were significantly different from others, as shown in Figs. 5 and 6. This suggested that these two stimuli may still appear as self-luminous at 2700 K, which was consistent to the findings that luminance cannot determine the transition from surface color to self-luminous for stimuli with different chromaticities [19,20].

It is worthwhile to note that the iPad display used in this experiment normally had a reflectance of 4 to 5% under the normal illumination. The reflected light due to the illumination may partially contribute to the change of viewing mode and the effect of adapting CCT under different adapting conditions. It will be interesting to carry out a similar experiment using self-luminous displays with an anti-reflective coating or electronic ink (E ink) displays to investigate whether the effects of adapting luminance and CCT will still significantly change the viewing mode.

4.2 Effect of adapting luminance and CCT on degree of chromatic adaptation

The degree of chromatic adaptation factor D under the four L_w levels—115, 300, 600, and 900 cd/m^2—and a Y_b of 40, as calculated using Eq. (1), would equal to 0.893, 0.952, 0.966, and 0.987. CAT16, with the D factor being set to 1, was used here to transform the tristimulus values of the adjusted stimuli under each adapting condition to the corresponding tristimulus values under the adapting condition at 6500 K with the same L_w level. The chromaticity differences between the transformed stimuli and the stimuli under the 6500 K condition in the CIE 1976 $u'_{10}v'_{10}$ chromaticity diagram are shown in Fig. 7. The larger the chromaticity difference, the lower the degree of chromatic adaptation caused by the adapting CCT, in comparison to 6500 K with the same luminance.

It can be observed in Fig. 7 that when the adapting conditions had a same adapting luminance, the 3000 K condition always caused the lowest degree of chromatic adaptation, followed by the 3500 K condition, and the degrees of chromatic adaptation under the adapting conditions at 5000 and 6500 K were similar. The effect of the adapting CCT, however, became less obvious with the increase of adapting luminance. Whether the effect of adapting CCT can be completely removed by further increasing the adapting luminance merits further investigations.

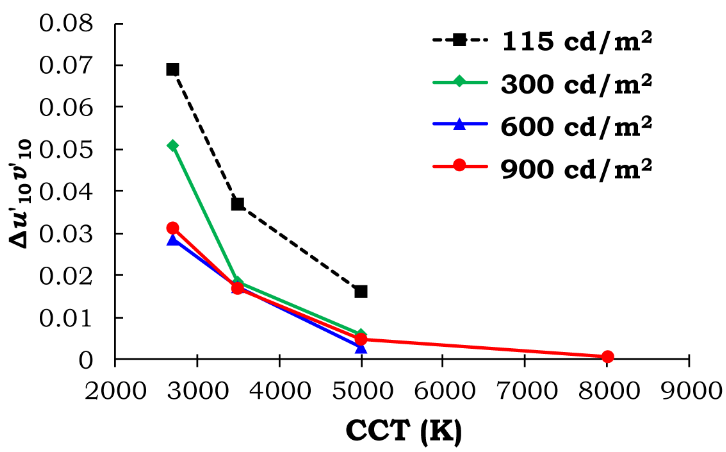

Fig. 7. Chromaticity differences between the average adjusted chromaticities under the 6500K adapting condition and those under other adapting CCTs, which were all transformed to their corresponding chromaticities under the 6500 K adapting condition using CAT16 with the degree of chromatic adaptation factor D being set to 1, at each adapting luminance level in the CIE 1976 $u'_{10}v'_{10}$ chromaticity diagram.

Moreover, when the stimuli when viewed in the self-luminous mode under the adapting conditions with an L_w of 115 cd/m^2, though it was obvious that the adapting CCT affected the appearance of the stimuli and the stimuli were still viewed as related colors, the effect of adapting CCT was less significant and the degrees of chromatic adaptation were much lower. It would also be interesting to investigate the effect of adapting CCT by further decreasing the adapting luminance and whether there exists a threshold of adapting luminance to make stimuli viewed as unrelated colors.

5. Conclusion

A psychophysical experiment was carried out to investigate the effects of adapting luminance and CCT on the degree of chromatic adaptation. Human observers were asked to adjust the color appearance of a stimulus, with a luminance from 50 to 350 cd/m^2, produced by a self-luminous display to make it appear the whitest under 17 adapting conditions, which were designed with systematically varied luminance (L_w from 115 to 900 cd/m^2) and CCT (from 2700 to 8000 K) levels.

When the adapting luminance was very low (i.e., L_w of 115 cd/m^2), the adjusted chromaticities to produce the whitest appearance were generally shifted along the Planckian locus towards a higher CCT level, which was similar to the findings in the past studies using self-luminous displays as the viewing medium. In contrast, when the adapting luminance was very high (i.e., L_w of 900 cd/m^2), the adjusted chromaticities to produce the whitest appearance were generally around those of the adapting conditions, which was similar to the findings in the past studies using reflective surface color samples as the viewing medium. Therefore, the effect of viewing medium (i.e., self-luminous displays versus reflective surface color samples) on white appearance and degree of chromatic adaptation, as reported in the past, was actually the effect viewing mode (i.e., surface mode versus self-luminous mode) caused by the change of adapting luminance.

Furthermore, when the adapting luminance was high enough (i.e., L_w of 300, 600, and 900 cd/m^2) to make the stimulus viewed in the surface mode, the adapting luminance and CCT levels were found to jointly affect the degree of chromatic adaptation. The effect of adapting luminance was found stronger when the adapting CCT was lower.

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