https://doi.org/10.2352/issn.2169-2629.2019.27.5

Degree of chromatic adaptation under adapting conditions with different luminance and chromaticities

Siyuan Chen and Minchen Wei*
The Hong Kong Polytechnic University
****Corresponding author: minchen.wei@polyu.edu.hk***

Abstract

Adapting chromaticities are not considered in characterizing the degree of chromatic adaptation in various chromatic adaptation transforms (CATs). Though several recent studies have clearly suggested that the effect of adapting chromaticities on degree of chromatic adaptation should not be ignored, these studies were only carried out under a single adapting luminance level. This study was carefully designed to systematically vary the adapting luminance and chromaticities to investigate whether the adapting luminance and chromaticities jointly affect the degree of chromatic adaptation. Human observers adjusted the color of a stimulus produced by a self-luminous display to make it appear the whitest under each of the 17 different adapting conditions. It was found the adapting chromaticities and luminance jointly affected the degree of chromatic adaptation. At a same adapting luminance level, the degree of chromatic adaptation was found lower under a lower adapting CCT (i.e., 2700 and 3500 K). A higher adapting luminance can significantly increase the degree of chromatic adaptation, especially when the adapting CCT was low (i.e., 2700 and 3500 K).

Introduction

Chromatic adaptation is an important mechanism in the human visual system. It helps to maintain a relative constant color appearance of stimuli under different adapting conditions by removing the color cast of the illumination to a certain extent, though the spectral compositions of the stimuli may significantly vary under different adapting conditions [1].

Great efforts have been made to develop models to characterize such an important mechanism, so that the color appearance of stimuli can be reproduced accurately and faithfully under different adapting conditions. The adapting luminance level has been found to have a large impact on chromatic adaptation, with a higher luminance level for a better ability to discount the effect of adapting conditions. Therefore, a degree of chromatic adaptation factor D, which is a function of adapting luminance, is included in some models (e.g., CAT02 and CAT16), to characterize the effect of adapting luminance on degree of chromatic adaptation [1].

Several recent studies, however, found that the degree of chromatic adaptation was also affected by the adapting chromaticities [2-7]. A lower degree of chromatic adaptation was found to happen under an adapting condition with a lower CCT (i.e., chromaticities were around the Planckian locus). These studies, however, were carried out under a single adapting luminance level, which cannot reveal whether the effects of adapting luminance and chromaticities were isolated.

This study was carefully designed to investigate how degree of chromatic adaptation is affected by adapting luminance and chromaticities by systematically varying these two factors simultaneously.

Methods

Apparatus

A 60 cm × 60 cm × 60 cm viewing booth, with interiors being painted using Munsell N7 paint, and a spectrally tunable LED device being placed above the viewing booth were used to create a uniform adapting field. A 45° viewing table was placed at the center of the viewing booth, with an iPad being placed at the center, as shown in Fig 1. The display of the iPad was covered by a Munsell N7 sheet, which had a 3 cm × 3 cm opening at the center and eight 3 cm × 3 cm Natural Color System (NCS) samples being attached around the opening. The NCS samples were used to help chromatic adaptation and the opening allowed the observers to perpendicularly see the display with a field of view (FOV) around 4° by keeping their chins on a rest.

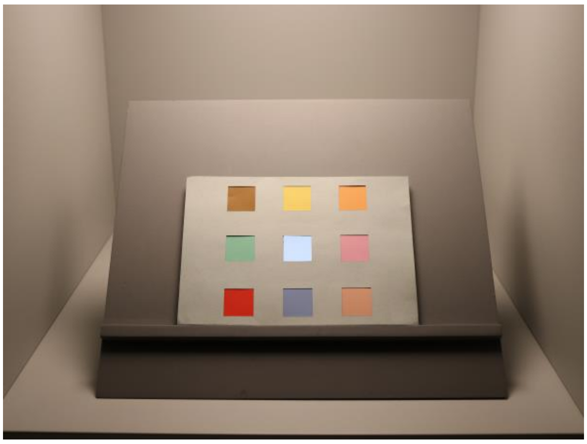

Figure 1 Photograph of the experiment setup

The iPad display was calibrated using the GOG model and the CIE 1964 10° Color Matching Functions (CMFs). An iOS APP was then programmed to allow the adjustment of the display color along the u'_{10} and v'_{10} axes in the CIE 1976 $u'_{10}v'_{10}$ chromaticity diagram at a constant luminance using the four arrow keys on a Bluetooth keyboard, with each press for a step 0.001 unit.

Adapting conditions and stimuli

Seventeen adapting conditions were created, with 16 conditions comprising four CCT levels (i.e., 2700, 3500, 5000, and 6500 K) and four adapting luminance levels (i.e., $L_w \approx 115$, 300, 600, and 900 cd/m^2) and an additional condition being 8000 K and 900 cd/m^2. These adapting conditions were created by carefully adjusting the intensities of the LED channels, so that the CIE General Color Rendering Index (CRI) were generally above 90. The adapting conditions were calibrated using a JETI Specbos 1411UV spectroradiometer and a Labsphere reflectance being placed at the center of the viewing table. Table 1 lists the colorimetric characteristics of the adapting conditions.

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
115	2700	(0.267,0.525)	2704	-0.0012	115.9	97.3
	3500	(0.236,0.516)	3516	+0.0030	116.1	97.9
	5000	(0.208,0.493)	4997	+0.0080	117.3	96.8
	6500	(0.196,0.471)	6514	+0.0054	116.7	97.4
300	2700	(0.269,0.526)	2679	-0.0009	300.0	94.8
	3500	(0.240,0.508)	3498	-0.0030	299.0	88.4
	5000	(0.215,0.484)	4993	-0.0020	302.0	93.9
	6500	(0.204,0.466)	6482	-0.0016	301.0	94.2
600	2700	(0.268,0.526)	2693	-0.0004	599.5	94.6
	3500	(0.240,0.511)	3477	-0.0004	604.0	90.0
	5000	(0.216,0.482)	4994	-0.0028	610.0	94.2
	6500	(0.202,0.468)	6491	+0.0008	609.5	94.3
900	2700	(0.269,0.529)	2670	+0.0009	900.1	94.5
	3500	(0.240,0.511)	3485	-0.0008	911.6	90.1
	5000	(0.215,0.482)	5042	-0.0024	907.7	93.6
	6500	(0.204,0.466)	6501	-0.0015	908.0	94.2
	8000	(0.197,0.453)	8018	-0.0018	910.3	94.1

The stimulus was produced by the iPad display, which was viewed through the center opening of the Munsell sheet. Six luminance levels (i.e., 100, 150, 200, 250, 300, and 350 cd/m^2) were created for the stimulus. The gamut of the display at each of these luminance level was verified to cover the chromaticities of the blackbody radiators between 2700 and 6500 K, which were the adapting chromaticities.

Observers and experimental procedures

Eight observers (seven males and one female) between 22 and 28 years of age (mean = 24.3, std. dev. = 2.3) completed the experiment. They all had a normal color vision, as tested using the Ishihara Color Vision Test.

Under each adapting condition, the observer first looked into the viewing booth for two minutes for chromatic adaptation. Then the experimenter placed the iPad, which was covered with the Munsell sheet and the eight NCS color samples, on the center of the viewing table. The luminance of the iPad was adjusted to one of the six levels and the color of the display was adjusted to be obviously non-white. The observer was instructed to use the four arrow keys to adjust the color of the display until it appeared the whitest to him or her. The same procedure was repeated for all the six display luminance levels and all the 17 adapting conditions. The orders of the adapting conditions and the display luminance levels were randomized.

Results

After the experiments, the spectral power distribution (SPD) of each stimulus that was adjusted by the observers was measured under the corresponding adapting condition, which considered the light emitted by the display and the light reflected by the display. These measured SPDs were used in the following analyses.

The measured luminance of the adjusted stimulus was 5.8% to 1.6% (mean = 4.38%, std. dev. = 0.0073) lower than the calibrated display luminance level, and the adjusted chromaticities were always far from the display gamut at the corresponding display luminance level.

Inter-observer variations

The inter-observer variations were characterized using the mean color difference form the mean (MCDM) in the CIE 1976 $u'_{10}v'_{10}$ chromaticity diagram by comparing the adjustments made by each observer and the average adjustments made by the observers (i.e., an average observer) under each adapting condition. As summarized in Table 2, the MCDM values were comparable to those in the several recent studies investigating white appearance and memory colors.

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

	115 cd/m^2	300 cd/m^2	600 cd/m^2	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

Average adjusted chromaticities

Figure 2 shows 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. The average chromaticities adjusted by the observers were also calculated in CAM02-UCS, as shown in Figure 3, which considers the effect of chromatic adaptation. The degree of chromatic adaptation factor D was set to 1 (note: the factor would equal to 0.893, 0.952, 0.966, and 0.987 for the four adapting luminance levels as calculated in CAT02, with a Y_b of 40). The distances between the average chromaticities adjusted by the observers and the origin (i.e., the adapting chromaticities) in the a'_{10}-b'_{10} plane are shown in Figure 4.

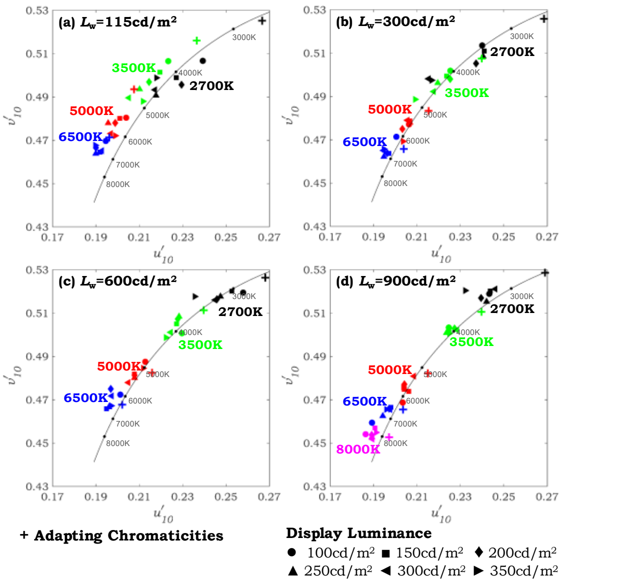

Figure 2 Average chromaticities of the stimuli adjusted by the observers at each display luminance level under each adpting condition in the CIE 1976 $u'_{10}v'_{10}$ chromaticity diagram. (a) L_w = 115 cd/m^2; (b) L_w = 300 cd/m^2; (c) L_w = 600 cd/m^2; (d) L_w = 900 cd/m^2.

It can be observed that the chromaticities adjusted by the observers were closer to those of the adapting conditions with an increase of the adapting luminance, especially when the adapting CCT was 2700 and 3500 K, which clearly suggested the effectiveness of a higher adapting luminance in improving the degree of chromatic adaptation. The distance between the chromaticities adjusted by the observers and the adapting chromaticities at 2700 and 3500 K, however, was never as close as those under the conditions at 5000 and 6500 K.

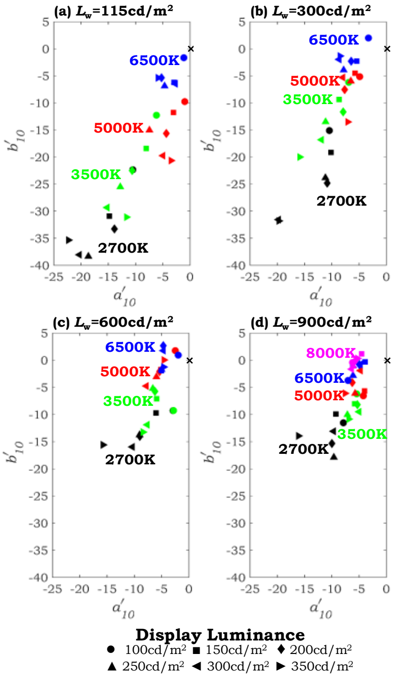

Figure 3 Average chromaticities of the stimuli adjusted by the observers at each display luminance level under each adapting condition in the a'$_{10}$-b'$_{10}$ plan of CAM02-UCS. (a) L_w = 115 cd/m^2; (b) L_w = 300 cd/m^2; (c) L_w = 600 cd/m^2; (d) L_w = 900 cd/m^2.

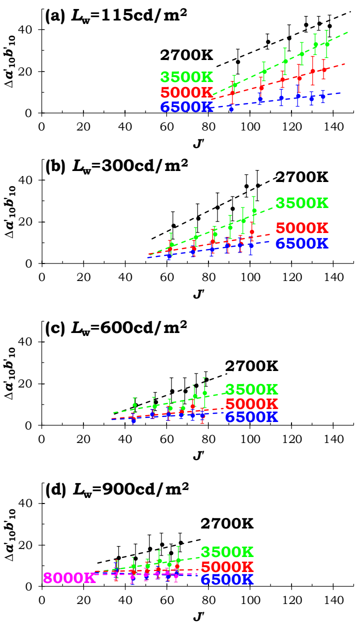

Figure 4 Chromaticity differences, together with the 95% confidence interval, between the average chromaticities of the stimuli adjusted by the observers and the origin in the a'$_{10}$-b'$_{10}$ plane of CAM02-UCS. (a) L_w = 115 cd/m^2; (b) L_w = 300 cd/m^2; (c) L_w = 600 cd/m^2; (d) L_w = 900 cd/m^2.

Discussion

Adapting luminance, viewing mode, and chromatic adaptation

The experiment used a same viewing medium (i.e., a self-luminous iPad) under different adapting luminance levels and all the observers were well aware of the fact that they were adjusting the color appearance of a stimulus produced by the display. The results at the two adapting luminance levels—L_w of 115 and 900 cd/m^2—were similar to those in many past studies using two different viewing media (i.e., self-luminous displays and surface color samples) [2, 4, 5, 6, 8-12]. Specifically, when the adapting conditions had an L_w of 115 cd/m^2, the chromaticities were generally shifted towards a higher CCT along the Planckian locus regardless of the adapting CCT, which was similar to those found in the studies using self-luminous displays [2, 6, 8, 9-12]. On the contrary, when the adapting conditions had an L_w of 900 cd/m^2, the adjusted chromaticities were generally around the adapting chromaticities, which was similar to those found in the studies using surface color samples [4-6, 11].

Therefore, the different chromaticities for producing a white appearance using surface color samples and self-luminous displays should be attributed to the different viewing modes instead of viewing media. In other words, the increase of the adapting luminance level from an L_w of 115 to 900 cd/m^2 changed the viewing mode from self-luminous to surface mode, which can also be observed from the J' values in Figure 4.

Adapting luminance, chromaticities and chromatic adaptation

To more directly investigate how adapting luminance and chromaticities affect degree of chromatic adaptation, the chromaticities adjusted under each adapting condition were transformed to those under the adapting condition at 6500 K with the same L_w level, with the D factor being set 1. The chromaticity differences between these transformed stimuli and the stimuli under the 6500 K condition in the CIE 1976 u'10v'10 chromaticity diagram were calculated and are shown in Figure 5.

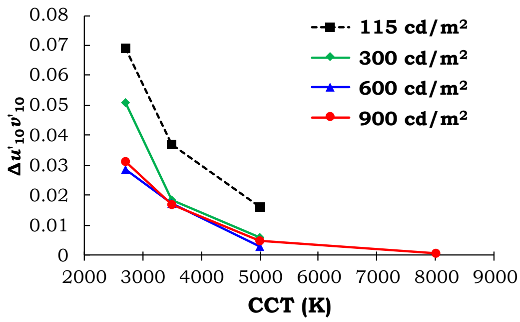

Figure 5 Chromaticity differences between the average adjusted chromaticities under the 6500K adapting condition and those under other adapting CCTs, which were all transformed to their corresponding chromaticities under the 6500 K adapting condition using CAT16 with the degree of chromatic adaptation factor D being set to 1, at each adapting luminance level in the CIE 1976 u'$_{10}$v'$_{10}$ chromaticity diagram.

It can be observed that when the adapting conditions had a same adapting luminance, the 2700 K condition always had 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 adapting chromaticities (i.e., 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.

Conclusion

A psychophysical study was carried out to investigate the effects of adapting luminance and chromaticities on the degree of chromatic adaptation. Human observers adjusted the color appearance of a stimulus, with a luminance from 50 to 300 cd/m^2, produced by a self-luminous display to make it appear the whitest under 17 adapting conditions. The adapting conditions were carefully designed with different adapting luminance and CCT levels.

Adapting luminance and chromaticities were found jointly affect the degree of chromatic adaptation. When the adapting CCT was 2700 and 3500 K, the degree of chromatic adaptation was found lower. And the effect of adapting luminance on degree of chromatic adaptation was found stronger when the adapting CCT was lower.

Funding

National Science Foundation of China (61975170).

References

[1] M. D. Fairchild, Color Appearance Models, 3rd ed. (John Wiley & Sons, 2013).

[2] H. P. Huang, M. Wei, and L. C. Ou. "White appearance of a tablet display under different ambient lighting conditions," Opt. Express, 26(4), 5018-5030 (2018).

[3] 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).

[4] M. Wei, S. Chen, H. P. Huang, and M. R. Luo. "Development of a whiteness formula for surface colors under an arbitrary light source," Opt. Express, 26(14), 18171-18181 (2018).

[5] M. Wei, S. Ma, Y. Wang, and M. R. Luo. "Evaluation of whiteness formulas for FWA and non-FWA whites,". J. Opt. Soc. Am, 34(4), 640-647 (2017).

[6] Q. Zhai and M. R. Luo. "Study of chromatic adaptation via neutral white matches on different viewing media," Opt. Express, 26(6), 7724-7739 (2018).

[7] Y. Zhu, Q. Zhai, and M. R. Luo. "Investigating chromatic adaptation via memory colour matching method on a display," in Proceedings of 26th Color and Imaging Conference (2018).

[8] R. Berns and M. Gorzynski. "Simulating surface colors on CRT displays: the importance of cognitive clues," in Proceedings of AIC Conference: Colour and Light (1991).

[9] E. Breneman. "Corresponding chromaticities for different states of adaptation to complex visual fields," J. Opt. Soc. Am, 4(6), 1115-1129 (1987).

[10] K. Choi and H. J. Suk. "Assessment of white for displays under dark- and chromatic-adapted conditions," Opt. Express, 24(25), 28945-28957 (2016).

[11] M. Fairchild. "Formulation and testing of an incomplete-chromatic-adaptation model," Color Res. Appl. 16(4), 243-250 (1991).

[12] G. High, P. Green, and P. Nussbaum. "Content-dependent adaptation in a soft proof matching experiment," in Proceedings of IS&T International Symposium on Electronic Imaging 2017, pp 67-75 (2017).

Author Biography

Siyuan Chen is currently a PhD candidate in Department of Building Services Engineering at the Hong Kong Polytechnic University.

Minchen Wei is an Assistant Professor in Department of Building Services Engineering at The Hong Kong Polytechnic University. He earned his Ph.D. degree from Department of Architectural Engineering at The Pennsylvania State University (University Park, PA, USA). He is currently a Division member representing Hong Kong in CIE Division 1: Vision and Color. His research mainly focused on color appearance and illumination.