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Time course chromatic adaptation under highly saturated illuminants

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Abstract

The goal of this study was to investigate the time course characteristics of chromatic adaptation under highly saturated illuminants. A psychophysical experiment with neutral matching method was conducted on a mobile display at different luminance levels. Models of chromatic adaptation degree against duration of time were fitted using a proportional rate growth function. The upper limit and growth rate of adaptation degree were studied. It was found that higher adapting luminance and lower display luminance led to higher degree and faster speed of chromatic adaptation. This study also proposed the time to achieve stable chromatic adaptation.

Introduction

Chromatic adaptation refers to the human visual system's capability to adjust to widely varying colours of illuminants in order to approximately maintain the consistency of perceived colour appearance[1,2]. It results from the change of sensitivity of the three types of cones to adapt to different illuminants, which takes a period of time to complete. Time course of chromatic adaptation can be divided into 3 stages: an extremely fast, a fast and a slower stage [3]. In this paper, the slow stage of chromatic adaptation over time was focused on.

Fairchild and Reniff [4] studied the time course of colour-appearance changes during chromatic adaptation at constant luminance. Three observers tracked achromatic appearance on a CRT display for six adapting chromaticity transitions, i.e. between D65 and 3 illuminants (A, D90, GRN). Proportion of adaptation was fitted as a function of adapting duration using a sum-of-two-exponentials function, corresponding to the two stages of adaptation, including one extremely rapid (a few seconds) and the other slower stage (approximately 1 min). They concluded that chromatic adaptation at constant luminance was 90% complete after approximately 60 s, which had been a guideline for the generally required adaptation time in visual experiments.

Rinner and Gegenfurtner [3] measured the three phases of chromatic adaptation. Observers performed achromatic matching for colour appearance and forced choice for colour discrimination on display along four different adapting colour directions, i.e. along the red–green and blue–yellow axes. They found that the slow phase had a half-life of about 20s and adaptation had reached steady state within 2 minutes. Spieringhs *et al.* [5] confirmed Rinner's conclusions. Their experimental results of time course chromatic adaptation could be fitted using Rinner's slow adaptation exponential model [3].

The above experiments gave quite different answers to the exact time required to reach complete adaptation. In the latest research, Gupta *et al.* [6] selected 14 test illuminants both on and off the daylight locus and performed achromatic adjustment experiments in immersive illuminants to study time course chromatic adaptation. They found that typically more than 5 minutes were required for the colour constancy index to stabilize. Differences rarely existed between the colour constancy index of illuminants on or off the daylight locus. Nevertheless, the test illuminants they used were still limited and did not cover the chromaticities close to the boundary of colour gamut.

Gupta *et al.* 's investigation [6] triggered the present work. The goal is to extend the gamut of their illuminants for further research. Furthermore, earlier studies showed that the degree of adaptation is affected by various parameters, including the luminance and chromaticity of adapting illuminants, the luminance of test stimuli [7-9]. A more chromatic illuminant resulted in a lower degree of chromatic adaptation [10, 11]. But few studies investigated highly saturated illuminants, especially those close to the boundary of colour gamut. Chromatic adaptation under such illuminants and its time-course effect has not been well studied.

In this study, a psychophysical experiment was carried out to study the time course chromatic adaptation using a neutral white matching method under different highly saturated illuminants. Different luminance levels of adapting illuminants and test stimuli were adopted in the experiment. The matching results revealed the degree of chromatic adaptation in a range of adaptation duration.

Experiment

Stimuli

A Huawei P20 pro mobile phone was used in the experiment. It was characterised using 3D Lookup Table (LUT) method, with a predictive accuracy of 1.77 in CIEDE2000 units evaluated using the 24 colours on the X-Rite Macbeth ColorChecker Chart. The display was placed vertically in a viewing cabinet and covered by a 4cm×4cm black mask to present a colour patch. The luminance of display was set to two fixed levels: high and low luminance levels of 90 and 9 cd/m^2, respectively.

Test illuminants

The experiments were conducted in a Thouslite viewing cabinet with an 18-channal spectrum tunable LED illumination system. L* of the background was 70. There were 5 ambient illuminants, including D65 together with 4 highly saturated illuminants close to the boundary of colour gamut. These were named red, yellow, green and blue. The illuminance measured in the center of cabinet was 140 lx, and its mean luminance was about 44 cd/m^2 using CIE 1931 2° standard colorimetric observer [12]. However, it was found when using CIE 1964 10° observer, luminance of the blue illuminant increased from 46.1 cd/m^2 to 72.3 cd/m^2, but little difference between the other test illuminants. So the other blue illuminant with lower luminance (marked as Blue-L) was designed to have similar luminance (44.3 cd/m^2) with other illuminants using CIE 1964 10° observer. Note that this illuminant was only used under the low display luminance condition.

Table 1 lists the chromaticity and luminance of test illuminants. Illuminant 'Blue' had similar luminance levels with other illuminants in 2°, while 'Blue-L' in 10°. Figure 1 shows the chromaticity coordinates of the adapting illuminants in CIE u'v' plane and Figure 2 shows the spectral power distributions (SPD) of the illuminants used. All the measurements were made using a JETI-Specbos 1211 spectroradiometer.

Table 1. Ambient illuminants chromaticity on CIE 1976 u'v' plane and luminance levels for CIE 2° and 10° observer respectively

	2°			10°		
	u'	v'	L (cd/m^2)	u'	v'	L (cd/m^2)
Red	0.579	0.512	44.5	0.549	0.516	45.2
Yellow	0.188	0.566	43.3	0.204	0.564	44.6
Green	0.037	0.553	44.4	0.045	0.563	51.5
Blue	0.206	0.133	46.1	0.187	0.173	72.3
D65	0.199	0.463	44.1	0.200	0.462	48.3
Blue-L	0.205	0.123	27.1	0.185	0.166	44.3

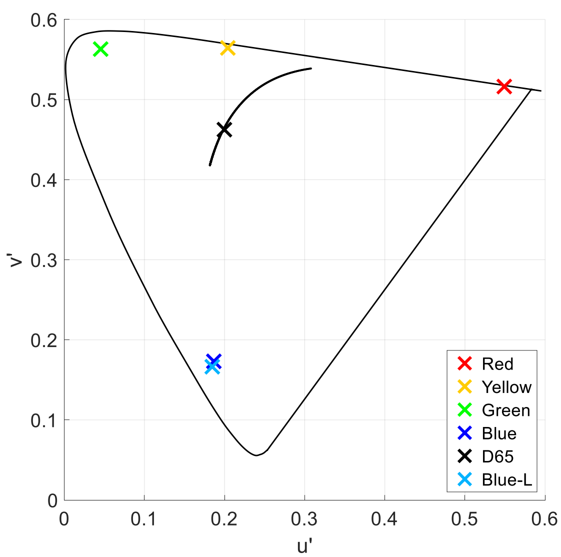

Figure 1. *Illuminants chromaticity on CIE 1976 u'v' plane (10°)*

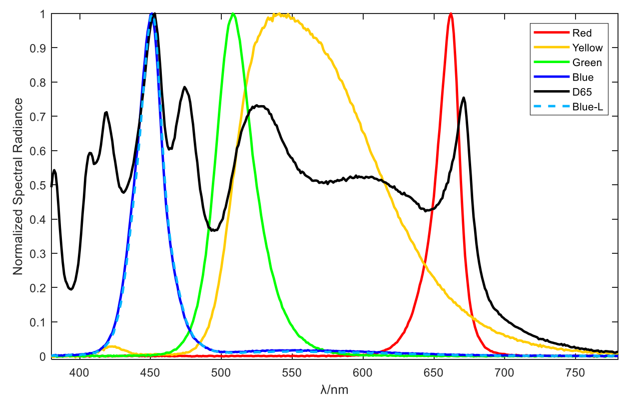

Figure 2. *Spectral power distribution of test adapting illuminants*

Observers and procedure

In total, 20 observers (7 males and 13 females) participated in the experiment. Their ages were ranged between 20 and 28 years old (mean = 24.2, std. dev. = 2.1). Eleven observers participated in the experiment of low display luminance and eleven observers participated in high display luminance, while two of them participated both. All the observers had normal colour vision according to Ishihara colour vision test.

During the experiment, observers sat on a chair and kept their eyes 50 cm from the display screen. They were asked to use a keyboard to adjust the colour on display to match neutral white, i.e. the colour does not possess of hue [13, 14]. The four arrow keys corresponded to the increase or decrease of CIELAB a* and b*. Starting point of each match had fixed L* of 50, C_{ab}* of 20, and random hue. Two luminance levels were applied. The lower level was achieved by using a neutral density filter with ND of 1.00. In the training session, observers were asked to perform some matches to ensure that they were confident to use the tool supplied and could finish one match within 1 minute. Figure 3 shows the experimental situation.

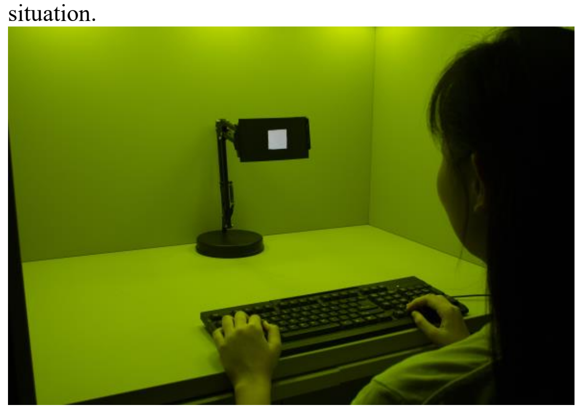

Figure 3. *Experimental situation*

In the real experiment, after 1-minute adaptation under D65, observers matched neutral white under D65 twice. Note that the D65 results were used to establish base-line. Then observers were asked to perform matching as soon as switch to a saturated illuminant. The time of an individual match for each observer was about 1 minute on average After completed one match, the display screen became dark, during which observers adapted to the ambient illuminant for about one minute. The total time of one match and adaptation was controlled at 2 minutes. This cycle (1-minute match and 1-minute adaptation) was repeated for 6 times. It took each observer about 11~12 minutes to complete under one illuminant. The sequence of test illuminants was randomly arranged. Between experiments of 2 test illuminants, observers took a 5-minute break and adaptation under D65. Totally, there were 594 matches, i.e. 11 observers × (high display luminance @ 4 illuminants + low display luminance @ 5 illuminants) × 6 repeats.

Results and Discussion

Observer variations

Observer variations were evaluated by calculating mean colour difference from mean (MCDM) using CIEDE2000 formula [15]. A higher MCDM value indicates a larger observer variation and less observer consistency.

Intra-observer variations were calculated using the repeated matches by each observer under D65. The MCDM values for high and low display luminance levels were 3.17 and 2.61 CIEDE2000 units, respectively.

Inter-observer variations were calculated between observers for each match under coloured illuminants. Figure 4 shows the tendency of inter-observer MCDM for 6 matches. It can be seen that a reduction of observer variations as duration was increased. This is expected due to more stable chromatic adaptation over time. The MCDM values of 6 matches for high and low display luminances were 5.27 and 6.22 CIEDE2000 units, respectively. Inter-observer variations were larger under low display luminance than that under high display luminance.

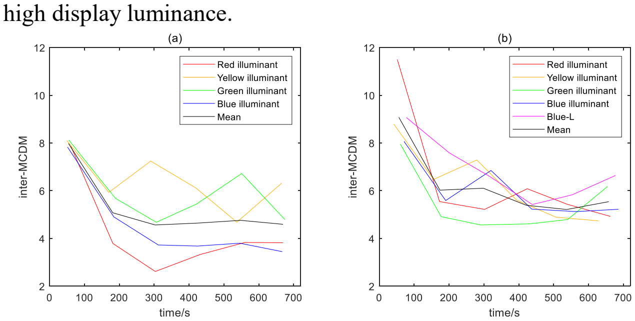

Figure.4 *Inter-observer variations (MCDM) in CIEDE2000 for 6 times of matches under different adapting illuminants and display luminance levels. (a) high display luminance, L= 90 cd/m^2, (b) low display luminance, L= 9 cd/m^2*

Matching end points

Figure 5 shows the matching results under different ambient illuminants and display luminance levels. As duration is increased, matching results shifted towards the chromaticity of test illuminants. It can be seen that matching results with low display luminance were much closer to the chromaticity of adapting illuminants, which indicates a more complete chromatic adaptation.

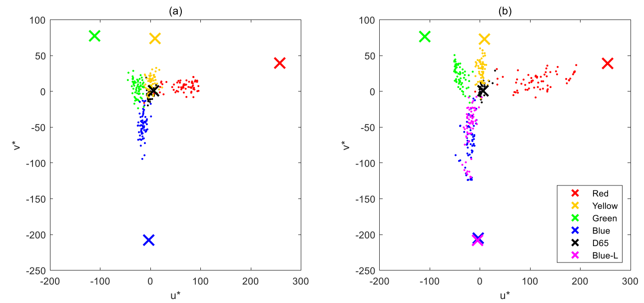

Figure 5. *Matching results under different ambient illuminants and 2 display luminance levels in CIELUV colour space. (a) high display luminance, (b) low display luminance. '×' represents the chromaticity of test illuminants*

Projected colour constancy index

Projected colour constancy index (pCCI) proposed by Gupta *et al.* [6] quantifies the degree of chromatic adaptation, ranged from 0 (no adaptation) to 1 (complete adaptation). Firstly calculate the projection of matching result to the line connecting the reference and test illuminant chromaticity in CIELUV colour space. Then pCCI was calculated as the ratio of the distance between the reference and projected point to that between the reference and test illuminant. In this experiment, the reference point was the neutral white matching results under D65, as base-line illuminant.

The pCCI values were calculated using each matching result. Figure 6 shows the error bars from 6 repeated matches under different ambient illuminants. The error bars represent standard error between observers. The results indicate observers performed less consistently with low display luminance, which was in agreement with the results of inter-observer variations.

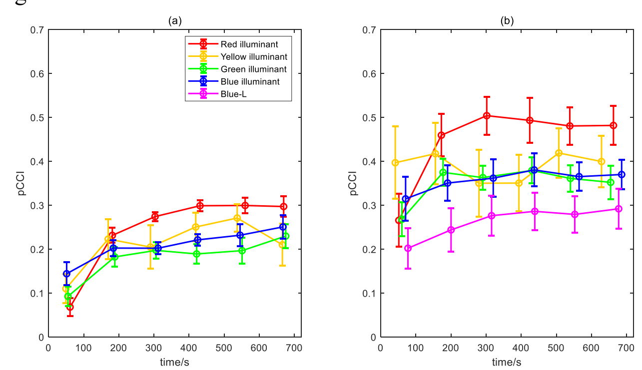

Figure 6. *Error bars (standard error) of 6 times matches under different ambient illuminants. (a) high display luminance. (b) low display luminance*

Statistical test was also conducted to show significant difference of pCCI between different test illuminants, between display luminance, and between adapting luminance levels. According to the ANOVA results, there were differences between 2 display luminance levels ($F(1,65)=256.186$, $p<0.0005$), and also between 4 test illuminants ($F(3,195)=10.617$, $p=0.002$). For the 2 adapting luminance levels of the blue test illuminant, there was also significant difference between the two levels ($p<0.0005$).

Finally, a proportional rate growth function was used to develop a model of pCCI, as given in Eq. (1), where t is the adaptation time, and a and k are parameters to be optimized, representing the upper limit and speed of adaptation respectively, as the model proposed by Gupta *et al.* [6].

$$pCCI(t) = a(1 - e^{-kt}) \quad (1)$$

Figure 7 plots the fitted time-course pCCI curves under different testing illuminants. It clearly shows some differences to reach complete adaptation between different test illuminants and luminance levels of display. It was found that under illuminants with the same chromaticity, pCCI values of low display luminance were obviously higher than that of high display luminance. This suggests a more complete chromatic adaptation for the former luminance.

Illuminants having different chromaticities (same luminance) also led to different pCCI values. For both display luminance levels, upper limits of pCCI values were the highest for red illuminant, followed by the yellow, blue and green illuminants. Note that here the blue illuminant refers to that having the same luminance with others calculated using the CIE 1931 2° standard colorimetric observer, instead of 'Blue-L'.

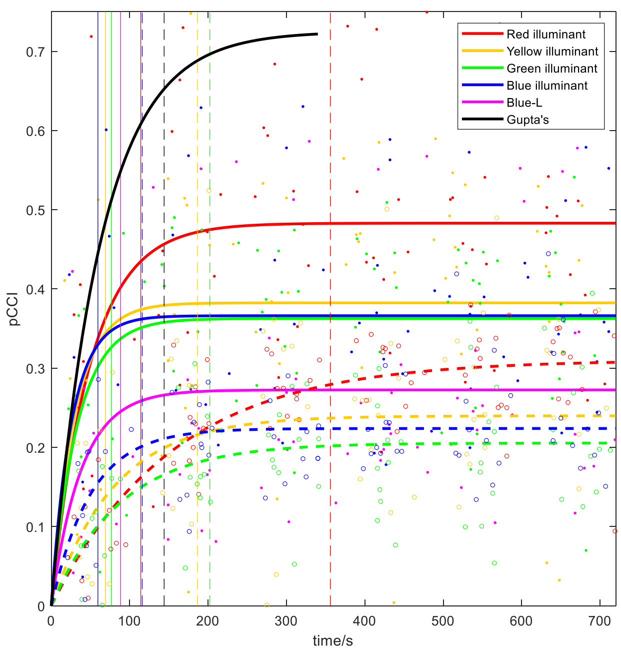

Figure 7. *Fitted time-course pCCI curves of different ambient illuminants. Solid curves: low display luminance (L=9cd/m²); dashed curves: high display luminance (L=90cd/m²). Vertical lines: the time reached 90% adaptation upper limit. Solid and circle dots represent the pCCI values for low and high display luminance levels, respectively. The black curve was the globally fitting result of pCCI growth function for the black surround in Gupta's study [6].*

The illuminant 'Blue-L' was only conducted at low display luminance because it was found large difference of luminance values calculated between 2° and 10° observers. Under condition of low display luminance, comparing the 2 blue illuminants with different luminance levels, it can be seen that the blue illuminant with lower luminance (Blue-L) had lower degree of adaptation. This agreed with the previous findings [8, 9]. Comparing the upper limit of pCCI values of the 2 blue illuminants with other illuminants, the blue illuminant (2°) had similar degree of adaptation with the others, while pCCI of 'Blue-L' (10°) was obviously lower. For high display luminance, the blue illuminant (2°) also had similar pCCI with the others. The present results show that illuminants with the same luminance levels in 2° had similar degree of chromatic adaptation.

The pCCI values reported here were smaller than those in Gupta *et al.*'s study drawn as black curve in Figure 7, suggesting a lower degree of chromatic adaptation in the present study. This could be caused by the different conditions of the two studies. Their experiments were conducted under immersive and less-saturated illuminants than ours, which could lead to higher degree of chromatic adaptation.

Speed of chromatic adaptation process

The time required to achieve 90% upper limit of adaptation implied the speed of chromatic adaptation. Table 2 lists the time to reach 90% adaptation degree for different test illuminants and 2 display luminance levels, which was also plotted as vertical lines in Figure 7. It was found that lower display luminance contributed to shorter adaptation time, i.e. faster adaptation speed to ambient illuminants. This could be due to the interference of the high luminance of display on observers' chromatic adaptation to ambient illuminants. To find out the relationship between the luminance of test illuminants and speed of chromatic adaptation, comparing the 2 blue illuminants, it can be seen that the blue illuminant with lower luminance (Blue-L) had longer adaptation time, i.e. lower adaptation speed. Moreover, the 90% adaptation time for different illuminants with the same adapting luminance followed the law: red > green > yellow > blue illuminant.

Table 2. The time required to achieve 90% upper limit of chromatic adaptation for different test illuminants and 2 display luminance levels

illuminant	low display luminance	high display luminance
Red	114 s	356 s
Yellow	69 s	186 s
Green	77 s	202 s
Blue	59 s	116 s
Blue-L	88 s	/

It can be seen from Table 2 that for low display luminance, about 1~2 minutes are required to achieve 90% adaptation for different adapting illuminants. For high display luminance, at least 2~3 minutes are needed. And it even takes about 6 minutes for red illuminants. This implies that more adaptation time is required at lower luminance of lights and higher luminance of display. The red illuminant required more adaption time than others.

From Figure 7, it can be seen that the 90% adaptation time in Gupta's study (see the black vertical dashed line) generally located between that of high and low display luminance levels in this study. It's reasonable from the view of the comparison of adapting illuminance and display luminance. On the one hand, the low display luminance in this study (9 cd/m²) was approximately equal to that in the Gupta *et al.*'s study (10 cd/m²), while the adapting illuminance in this study (140 lx) was higher than Gupta's (100 lx). So that the adaptation period at low display luminance in this study was shorter than that of Gupta. On the other hand, the high display luminance in this study was up to 90 cd/m² and became the main factor, causing slower adaptation speed than that of Gupta.

Moveover, Gupta *et al.* concluded that the adaptation progress did not differ significantly between test illuminants with moderate or saturated chromaticities. However, their illuminants exclude the extremely saturated colours close to the boundary of colour gamut as used in the present experiment.

Comparing the low display luminance level of this study with Fairchild's results [4], their experiment had lower adapting luminance (having a mean of 25 cd/m^2) and higher display luminance (25 cd/m^2) than this study, which were both factors against the adaptation process, but actually the time reached 90% chromatic adaptation in Fairchild's study (60s) was much shorter than that of this study. Considering the much more saturated adapting illuminants used in this study, a possible conclusion could be made that higher saturated illuminants might lead to longer adaptation time.

For the future works, it is worthwhile to include more adapting illuminants with different saturation levels and chromaticities, and further study their effect on chromatic adaptation degree and stable time.

Conclusions

A psychophysical experiment was carried out to study the time course of chromatic adaptation under highly saturated adapting illuminants. Observers were asked to match their neutral white in a period of about 12 minutes under each test illuminant. The results were used to fit models of time course in term of degree of chromatic adaptation. It was found that higher adapting luminance and lower display luminance can result in a more complete and faster speed of chromatic adaptation. These highly saturated illuminants with different chromaticities also showed different performance. Approximately 1~2 minutes and 2~6 minutes were needed to complete 90% degree of chromatic adaptation for low and high display luminance levels, respectively. Further experiments will be carried out to test more illuminants with wider range of chromaticity distributions and more luminance levels.

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