https://doi.org/10.2352/ISSN.2169-2629.2018.26.313

Investigating Chromatic Adaptation via Memory Colour Matching Method on a Display

Yuechen, Zhu[1], Qiyan, Zhai[1], Ming Ronnier, Luo[1,2*]
[1]State Key Laboratory of Modern Optical Instrumentation; Zhejiang University, Hangzhou, China
[2]School of Design, University of Leeds, Leeds LS2 9JT, UK
[*]Corresponding author: m.r.luo@zju.edu.cn

Abstract

An experiment was carried out to investigate the incomplete chromatic adaptation on a self-luminous display using memory colour matching method. The goal was to distinguish between the chromatic adaptation and simultaneous colour contrast and develop models to predict each effect. Five adapting fields derived from a pilot visual matching experiment corresponding to four CCTs (2856K, 4500K, 6500K, 9000K) and fourteen familiar objects were studied. Twenty normal colour vision observers participated in the experiment. In total, 1400 matches were accumulated. Seventy corresponding pairs were obtained. The dataset was also conducted to test various CATs and to verify the D function in CAT02. The results showed that the chromatic adaptation for self-luminous display is more incomplete than that in the real scene, but the trend between CCT and degree of adaptation is consistent with our previous study.

Introduction

Chromatic adaptation transform (CAT) is extensively used in many industrial applications, including colour change index, colour appearance model and the prediction of the colour rendering of sources. The purpose is to predict the same colour appearance under different illuminants, that is known as *'corresponding colour'* [1-2].

Colour adaptation is a visual effect which is widely studied in recent years. The work before 2004 was well summarized in CIE Publication 106:2004 named 'A review of chromatic adaptation transform' [3]. It covers different experimental techniques for describing chromatic adaptation, various experimental data sets commonly used to evaluate chromatic adaptation transforms. Most of the chromatic adaptation transforms including full equations and testing different transformations are reviewed. The results show that those having the sharp sensors such as CAT02, CMCCAT2000 outperformed the others. The former has been widely used in different applications. Recently, Li *et al.* developed CAT16 by removing some mathematical problems in CAT02 [4]. Therefore, CIECAM02 was also revised to become CAM16 due to the change from the imbedded CAT02 to CAT16.

More recently, Smet *et al.* conducted new achromatic-matching experiments using real 3D objects via memory colour matching method [5-8]. The results revealed that the incomplete adaptation factor (*D*) in CAT02 is insufficient due to a lake of consideration of the colour of the adopting illuminant as they found illuminants closer to the daylight would have a more complete adaptation. It indicates that CAT02 can be improved to revisit the chromaticity of illuminants and media/surround conditions.

Memory colours deviate slightly but significantly in the same direction from the natural colour (higher chroma) [9-10]. Anya's study indicated that shape, texture and gloss each improve memory colour accuracy comparing to uniformly coloured patches [11-12]. Thus, enhancing the naturalness of the stimulus improves the accuracy and precision of memory colour. For this reason, the present work adopted memory colour matching method using 2-D images. The goal is to separate the chromatic adaptation from the simultaneous colour contrast, and produce a new dataset of corresponding colours to test existing CATs and verify the *D* function in CAT02.

Experimental

Preliminary experiment

The experiment is designed to produce a new corresponding dataset under four different CCTs (2856K, 4500K, 6500K, 9000K) to investigate the chromatic adaptation. However, it was found that especially for illuminants having low CCTs, the background colours on display are much more colourful than those viewed under in the viewing cabinet, although their CCTs and luminance were closely matched. Hence, a preliminary experiment was conducted to match the grey backgrounds on the display to those in a viewing cabinet. The method is similar to that used by Gu *et al.* [13].

Five normal colour vision observers (3 males and 2 females) participated in the experiment. The cabinet and the display were placed side by side, each observer sat in front of them individually and viewed the middle area of the bottom of the cabinet to adjust the colour on the display until they looked visually the same. Observers used a keyboard to adjust the chroma and hue of the colour on the display with a constant lightness which was the same as the cabinet.

Table 1. The observer variations of preliminary experiment.

	MCDM ($\Delta u'v'$)		MCDM (ΔE_{00c})	
	inter	intra	inter	intra
2856K	0.0028	0.0014	0.65	0.40
4500K	0.0025	0.0018	1.05	0.79
6500K	0.0041	0.0016	1.99	0.95
9000K	0.0025	0.0018	1.03	0.63
average	0.0030	0.0017	1.18	0.69

Table 2. Visual matching results of preliminary experiment.

CCT of cabinet	2856K	4500K	6500K	9000K
Matching result	3119K	4966K	6902K	9719K

The observer variation of the result was assessed by calculating Mean Colour Difference from the Mean (MCDM). The colour difference was calculated in CIE 1976 $u'v'$ plane and also CIEDE2000 with zero luminance difference (ΔE_{00c}). The overall MCDM was found to be 0.0030 and 0.0017 of $\Delta u'v'$ unit for inter-and intra-observer variations respectively. Table 1 and Table 2 show the values of MCDM and results for each CCT. Figure 1 indicates that the colours were less colourful on display comparing to the cabinet, and a lower CCT would have a larger difference between the calculated values and visual matched values.

The shifts represent an incomplete adaptation especially for low CCTs. The visual matched values of 4 CCTs and the calculated value of the lowest CCT (2856K) were used in the main experiment.

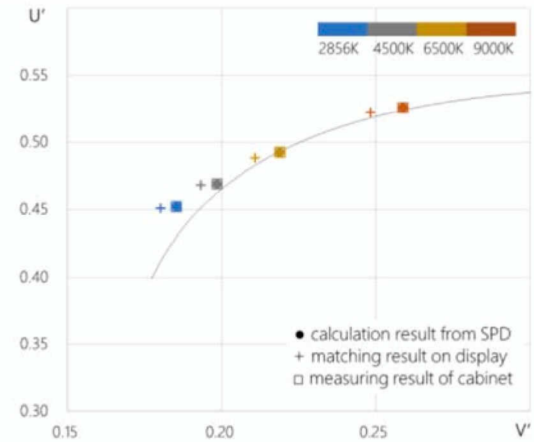


Figure 1. The results of the preliminary experiment plotted in CIE 1976 u'v' diagram.

Main experiment

Objects and adapting fields selection

The criteria for selecting the memory colours mainly include the familiarity of objects and the color distribution in hue circle [14]. Considering these criteria, fourteen objects were studied which included nine familiar objects (red apple, tomato, blueberry, sky, green pepper, grass, banana, lemon, eggplant) and five coloured cubes (pure red, pure yellow, pure green, pure blue, neutral grey) [15], Figure 2 shows the images of objects used in the experiments.

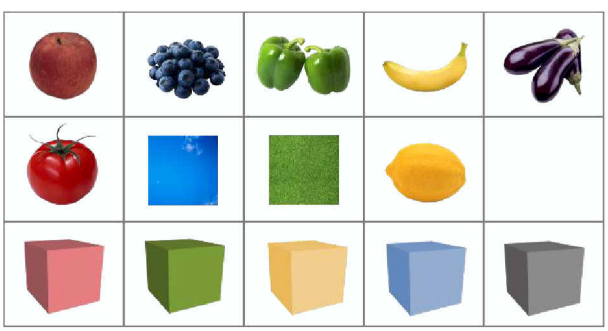


Figure 2. The images of test objects used in the experiments.

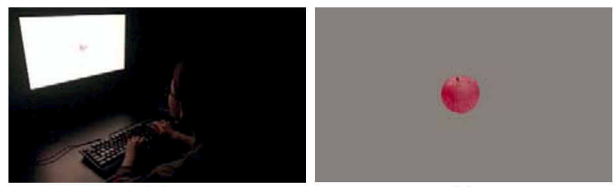
Five adapting fields (2856K, 3119K, 4966K, 6902K and 9719K) derived from the pilot visual matching experiment were studied.

Experimental design

The scaling technique used here is the memory matching method that involves the long-term memory colours of familiar objects as internal references [14]. The experiment was conducted in a dark room without ambient light. The work was similar to that of Smet *et al.* by adjusting the colour of familiar objects on a calibrated EIZO-CG243W display (size: 24.1", luminous level: 125 cd/m^2).

For each adapting field, observers sitting at a distance of 60cm away from the monitor were asked to adapt to the viewing conditions for 1 min. After that, observers got a grey image (5 degrees) of certain object and adjusted the colour of it to match their memory colours by changing the chromatic (only hue and chroma) differences via a keyboard. Once the observer confirmed the matching colour, the next grey image was presented, and so on. Note that in coloured cube sessions, observers only adjust the hue of the colour with constant chroma and lightness. Twenty normal colour vision observers participated in the experiment including twelve males and eight females. In total, 1400 matches were accumulated, i.e. 5 adapting fields × 14 objects × 20 observers.

Figure 3a shows the experimental situation. And Figure 3b shows operational interface was designed by Matlab Graphical User Interface.



(a) (b)

Figure 3. Experiment setting. (a) The experimental situation; (b) Operational interface designed by Matlab Graphical User Interface.

Result & Discussion

Observer variation

Mean Colour Difference from the Mean (MCDM) were also calculated to represent the observer variation. The CIEa^*b^* and CIEDE2000 with zero luminance difference (ΔE_{00c}) [16] were used to calculate the colour difference, which means ΔL=0 in the calculation. Figure 4 and Table 3 show the inter observer variation characterized by MCDM. The overall MCDM values are 5.06 ΔE_{00c} and 10.36 ΔE^*_{ab} for the inter-observer variation. Comparing to previous studies which used memory colours as internal references, the MCDM value of this experiment is considered to be quite small, e.g. the MCDM was 16 ΔE^*_{ab} for the inter-observer variations of Zhu *et al.*'s study, and 5.9 ΔE_{00c} of Zhai *et al.*'s study. Hence, a reliable corresponding dataset based on memory matching method is produced here.

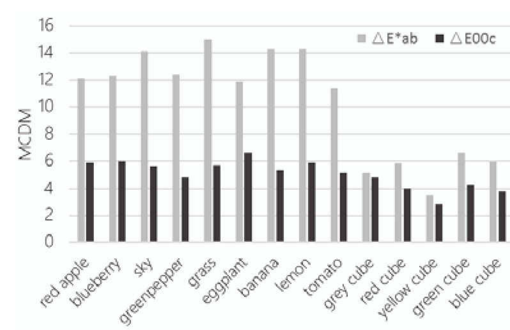


Figure 4. The inter observer variation characterized by MCDM for each object.

It can be found the results of 5 coloured cubes achieved less MCDM values than the other objects, because only hue values could be adjusted for the cube centres. It implies that observer variations decrease when the attributes decrease as expected.

Table 3. The inter observer variation characterized by MCDM.

MCDM	9 Objects	5 Cubes	Combined
ΔE^*_{ab}	13.09	5.44	10.36
ΔE_{00c}	5.68	3.94	5.06

Corresponding colours plotted in colour space

Figure 5 shows the results of corresponding colours plotted in CIECAM02 $a'b'$. Note that reference white ($X_wY_wZ_w$) is different for each adapting field during the calculation process. Taking corresponding reference white for each CCT to calculate the colour coordinates presupposed '$D = 1$'.

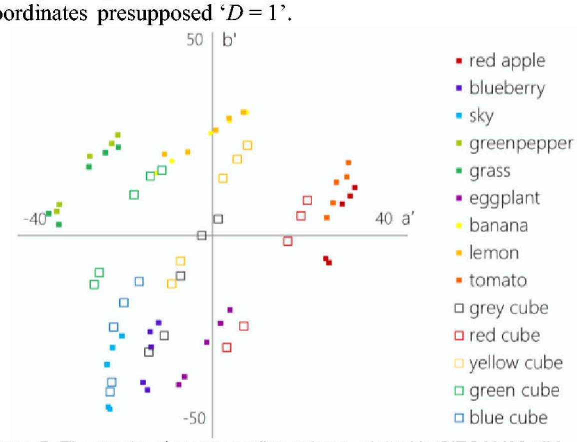


Figure 5. The results of corresponding colours, plotted in CIECAM02 a'b'.

Figure 6 shows that the adaptation is incomplete especially for low CCTs, i.e. their grey cube results are long way off the neutral point, the other cubes have the same trend. This confirms that degree of adaptation is affected by chromaticity of the illuminant.

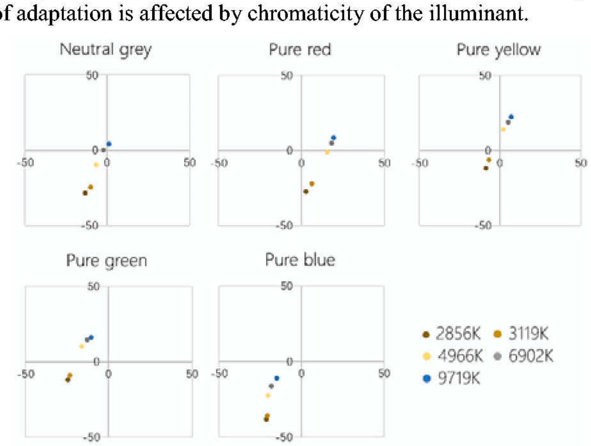


Figure 6. The results of coloured cubes (Neutral grey, Pure red, Pure yellow, Pure green and Pure blue respectively).

Testing D factor in one-step CAT02

The results indicate that chromatic adaptation is incomplete and CAT02 can be improved to revisit the chromaticity of illuminants and media/surround conditions [5-6]. The new dataset in this study was first used to test one-step CAT02 chromatic adaptation transform with optimized D. Table 4 shows optimized D values for each CCT.

It can be found that chromatic adaptation is extremely incomplete especially for low CCTs. While Figure 7 shows that a similar trend of optimized D can be found between present study and Zhai and Luo's result.

Table 4. Optimized *D* for one-step CAT02.

	2856K	3119K	4966K	9719K
D (optimized)	0.07	0.1	0.24	0.32

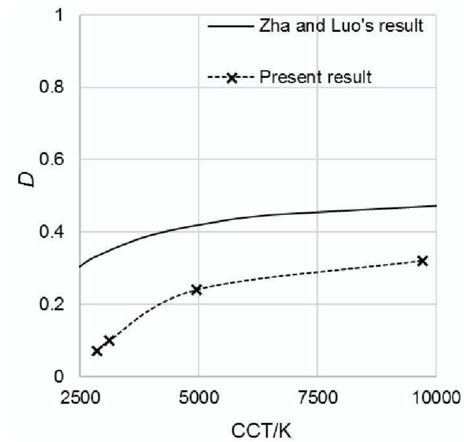


Figure 7. Optimized D on CCT values comparing with Zhai and Luo's study.

Testing D factor in two-step CAT02

The dataset was also used to test two-step CAT02 chromatic adaptation transform with different D functions, including Smet's and Zhai and Luo's together with $D = 1$, and derive optimized D values for each adapting field.

The results of grey cube and combined data were analysed. Four pairs of corresponding colours (2856K, 3119K, 4966K, and 9719K) including unitary and memory colours were formed between data from 6902K and the other CCTs. The degree of adaptation is judged by colour difference using CIEDE2000 without lightness difference (ΔE_{00c}). Equal-energy white (luminous level: 125 cd/m^2) was used as the baseline illuminant in the calculation.

Testing optimized D and $D = 1$

Table 5 shows optimized D values, which means the greatest predictive performance (i.e. a minimum colour difference) that can be obtained. Table 6 lists colour difference calculated by ΔE_{00c}.

Table 5. Optimized *D* for two-step CAT02 (*D1* for step 1, *D2* for step 2).

	2856K		3119K		4966K		9719K	
D (optimized)	*D1*	*D2*	*D1*	*D2*	*D1*	*D2*	*D1*	*D2*
	0.05	0.46	0.05	0.39	0.19	0.27	0.38	0.45

Table 6. The predictive performance of Optimized *D* and *D* = 1 in terms of ΔE_{00c}.

	2856K	3119K	4966K	9719K	mean
D = 1	17.71	15.84	4.52	3.32	10.3
D = optimized (one-step)	3.18	2.63	1.06	1.05	2.0
D = optimized (two-step)	2.34	2.09	0.98	1.05	1.6

Testing Smet's D function

D factor in Smet's function defined by Equation (1).

$$D_s = e^{-(3912\times(\frac{1}{CCT}-\frac{1}{6795}))^2} \quad (1)$$

Table 7 shows the performance of Smet's function. Original D_s means the D calculated directly from Smet's function, and an optimized coefficient was derived to obtain a best performance for each adapting field, which means a minimum colour difference.

Table 7. The predictive performance of Smet's function in terms of ΔE_{00c}.

Smet's function (CCT)		2856K	3119K	4966K	9719K	mean
original D_s	combined	11.25	11.3	4.43	3.06	7.5
	grey cube	16.84	15.15	7.88	4.92	11.2
0.20 x D_s	combined	2.91	2.47	1.09	1.20	1.9
0.24 x D_s	grey cube	3.08	4.56	1.49	1.89	2.8

Testing Zhai and Luo's *D* function

D factor in Zhai and Luo's function defined by Equation (2) and Equation (3).

$$D_{z1} = 0.723\left(1 - \frac{1116}{CCT} + 846 \times Duv - 49266 \times \frac{Duv}{CCT}\right) \quad (2)$$

$$D_{z2} = 28u'^2 - 30.19v'^2 - 24.11u'v' - 1.78u' + 32.58v' - 6.52 \quad (3)$$

Table 8 shows the performance of Zhai and Luo's function. Original D_{z1} means the D calculated directly from Equation (2) using CCT, while D_{z2} means the D calculated directly from Equation (3) using u'v', an optimized coefficient was derived to obtain a best performance for each adapting field, which means a minimum colour difference.

Table 8. The predictive performance of Zhai and Luo's function in terms of ΔE_{00c}.

Zhai and Luo's function		2856K	3119K	4966K	9719K	mean
original D_{z1} (CCT)	combined	8.51	7.51	2.29	2.07	5.1
	grey cube	14.19	11	4.16	2.83	8.0
0.26 x D_{z1}	combined	3.06	2.49	1.19	1.21	2.0
0.33 x D_{z1}	grey cube	3.99	4.94	1.63	1.75	3.1
Original D_{z2} (u'v')	combined	8.00	7.08	2.41	1.92	4.9
	grey cube	13.40	10.24	4.38	2.52	7.6
0.28x D_{z2}	combined	3.01	2.46	1.13	1.19	1.9
0.35 x D_{z2}	grey cube	3.78	4.71	1.48	1.73	2.9

Conclusion

The typical method used to collect corresponding data is short-term memory matching between two illuminant conditions. Memory matching method has also been widely used. It has the advantages such as more complete adaptation with no switching between two illumination fields, easy to perform the matching task. .

The new dataset accumulated here was used to test CAT02 chromatic adaptation transform with different D functions, including Smet's, and Zhai and Luo's using $D = 1$. The mean error of predictions were 5.8, 7.5 and 10.3 ΔE_{00c} units respectively. By multiplying 0.25 to the former two D functions, the ΔE_{00c} values reduced to about 2 units. This indicates that the adaptation is much more incomplete here comparing with those found in the earlier work. This could be due to the use of memory matching method on display under dark surround.

Current results showed a low degree of chromatic adaptation. However, the trend of CCT vs D (Figure 7) using display colours was found to be similar to our earlier experiment by Zhai and Luo. The chromatic adaptation is a complicated psychophysical phenomenon. Many experimental parameters could affect the degree of adaptation such as differences between object and display mode, and between object or patch, artificial uniform and non-uniform, or real uniform and non-uniform background for display viewing. The present results showed a lower degree of adaptation than the earlier work. This could be due to the object displayed against a uniform artificial background. May be a more natural image or multi-patches background could improve the degree of adaptation. The future work is required to conduct an experiment using real object and real background on display to investigate the chromatic adaptation .

In addition to chromatic adaptation, the colour appearance is also affected by simultaneous colour contrast. A large scale has been carried out and the results will be reported elsewhere.

References

[1] Von Kries, "Chromatic adaptation," Jour. Festschrift der Albrecht-Ludwigs-Universität, 145-158,1902.

[2] C. Li, M. R. Luo, B. Rigg, and R. W. G. Hunt, "CMC 2000 chromatic adaptation transform: CMCCAT2000," Jour. Color. Res. Appl.27, 49-58 (2002).

[3] CIE160-2004, "A review of chromatic adaptation transforms" (CIE, Vienna, 2004).

[4] Li C, Li Z, Wang Z, et al. "Comprehensive color solutions: CAM16, CAT16, and CAM16 - UCS," Jour. Color Research & Application, 42(1), 2017.

[5] Smet K A, Zhai Q, Luo M R, et al. "Study of chromatic adaptation using memory color matches, Part I: neutral illuminants," Jour. Optics Express, 25(7):7732, 2017.

[6] Smet K A, Zhai Q, Luo M R, et al. "Study of chromatic adaptation using memory color matches, Part II: colored illuminants," Jour. Optics Express, 25(7):8350-8365, 2017.

[7] Zhai Q, Luo M R, et al. "Modelling Incomplete Chromatic Adaptation and Colour Contrast Using Memory Colour," in Color and Imaging Conference, 2016.

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

[9] Smet K, Ryckaert W R, Pointer M R, et al. "Colour appearance rating of familiar real objects," Jour. Color Research & Application, 36(3):192–200, 2011.

[10] Olkkonen M, Hansen T, Gegenfurtner K R, "Color appearance of familiar objects: effects of object shape, texture, and illumination changes," Jour. J Vis, 8(5):13.1, 2004.

[11] Vurro M, Ling Y, Hurlbert A C, "Memory color of natural familiar objects: effects of surface texture and 3-D shape," Jour. Journal of Vision, 13(7):20, 2013.

[12] Hurlbert A, Vurro M, Ling Y, "Colour constancy of polychromatic surfaces," Jour. Journal of Vision, 8(6):1101-1101, 2008.

[13] Gu H T, Luo M R, Liu X Y. "Testing different colour rendering metrics using colour difference data," Jour. Lighting Research & Technology, 49(5), 2016.

[14] Zhu Y, Luo M R, Fischer S, et al. "Long-term memory color investigation: culture effect and experimental setting factors," Jour. Journal of the Optical Society of America A Optics Image Science & Vision, 34(10):1757, 2017.

[15] Kevin A G, Geert D, Peter H. "Chromaticity of unique white in object mode," Jour. Optics Express, 22(21):25830-41, 2014.

[16] Luo M R, Cui G, Rigg B. "The development of the CIE 2000 colour - difference formula: CIEDE2000," Jour. Color Research &.

Author Biography

Yuechen Zhu received her bachelor degree from College of Electronics and Information Engineering, Sichuan University, Chengdu, China. Now she is currently a master student at Department of Optical Engineering, Zhejiang University, Hangzhou, China. Her research interests include colour science and lighting engineering.