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Modelling Incomplete Chromatic Adaptation and Colour Contrast Using Memory Colour

Qiyan Zhai[1], M. Ronnier Luo*[1, 3], Peter Hanselaer[2], Kevin A.G. Smet[2]
[1] State Key Laboratory of Modern Optical Instrumentation, Zhejiang University, Hangzhou, China
[2] ESAT/Light & Lighting Laboratory, KU Leuven, Ghent, Belgium; [3] School of Design, University of Leeds, Leeds, UK

****m.r.luo@leeds.ac.uk***

Abstract

The chromatic adaptation and colour contrast cause the colour appearance shift according to the adapting illuminant and background, respectively. It is difficult to distinguish between these effects because they all have an impact on the colour appearance of object. An experiment was conducted using memory colour matching approach in real scene at a high luminance level of various sources on the blackbody locus and some saturated colours. The results were used to develop two kinds of models for the incomplete adaptation factor (D) in CAT02. The necessity of a target dependent correction was discussed.

Introduction

Chromatic adaptation, the adaptation of an observer's visual system to the colour of the illumination, causes a colour appearance shift. Over the years, many Chromatic Adaptation Transforms (CAT) [1-3] have been developed, including the widely used CAT02 [4] embedded in CIECAM02 [5]. CAT02 is a chromatic adaptation transform of the von Kries type applied in a sharpened sensor space instead of a regular cone space. In many viewing conditions, adaptation is not complete. Incomplete adaptation is estimated using the degree of adaptation factor D [3-5] which is, in the CAT02 transform, given by equation (1):

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

where$F$ is a factor dependent on the surround conditions and L_A is the luminance (cdm-2) of adapting field. D varies from 0 to 1 for no to full adaptation respectively. Note that possible surround conditions in CAT02 include dark, dim and average such as cinema, projected image in classroom, and office conditions. It can be seen that D is only affected by the luminance level regardless of the chromaticity of the adapting field. However, CAT02 was derived using corresponding colour datasets with adaptive field chromaticities under widely used illuminants in the surface colour industry (e.g. A, D50 and D65). For adapting fields with systematic variation across blackbody locus and high chroma, especially chromaticities far away from the blackbody locus (Duv>0.02), few investigation has been carried out.

According to daily life experience, one does not adapt fully to very high chroma environments, no matter how long the adaptation time and how bright the environment is. E.g. 'white' objects will retain a yellowish colour appearance under warm-white lighting. One can also notice that when looking at a target on a coloured background, the colour appearance of the target will be largely changed during the first few moments. While this could be due to very fast acting chromatic adaptation processes [6], it is likely more to do with higher simultaneous contrast. Figure 1 shows that the same two small center squares, physically surrounded by two different backgrounds, have a different colour appearance. The colour contrast effect describes how the appearance of a target colour is affected by its background colour [7, 8]. Many works have been done over decades [7, 9], however, a reliable colour contrast function is missing from Colour Appearance Models (CAM) such as CIECAM02 [5, 10]. There were two main theories in the previous investigations on colour contrast [11-14]. Firstly, the contrast effect works similar to chromatic adaptation with a colour appearance shift of the target colour based only on the background chromaticity (and luminance), which means it is target independent. A CAT could be modified to describe the colour contrast effect according to this assumption. Thesecond is the so-called simultaneous colour contrast of surface colour which is target dependent. The larger the colour difference between the target and the background colour,the less the effect of appearance change will be [13 ,14]. Changes in background colour due to illumination changes could therefore affect the colour appearance of objects through both the process of chromatic adaptation and simultaneous contrast [15].

Figure 1. The colour contrast effect

To study the performance of CAT02 under both neutral and coloured /illumination, and with the aim of developing more generic models, corresponding colour data was obtained in memory colour matching experiments using real 3D objects against 12 background pairs (with illuminant E as reference). Because both chromatic adaptation and colour contrast effects have an impact on the colour appearance of objects, it is hard to separate them in a corresponding colour experiment without unrealistic viewing conditions or one would need a complex background where background colour and adapting colour are usually the same. The target independent effect of colour contrast had been taken into account as a part of (incomplete) chromatic adaptation. The necessity of a target dependent correction was also discussed.

Method

Memory Colour Matching in a Real Scene

A Memory Colour Matching (MCM) approach was used to collect corresponding colour under different background or adapting colours [16]. MCM involves observers adjusting the colour appearance of the familiar object stimulus presented under each adaptive or background condition until it matches what they remember it should appear. Note that the MCM is a method of colour appearance matching, not surface matching [11] and has been successfully used to obtain memory colours [17] for use as internal reference in colour rendition evaluation [18, 19].

The experimental setup consisted of a 3D stage including white, grey and black objects and a large white panel as background. The target object in the center of the scene served as test stimulus. A colour calibrated data projector was used as light source to enable separate colour control of the background and test stimulus (target colour), (Figure 2). The size of background in the scene had a field of view of 70°. The 3D background stage was used as the adapting field. Meanwhile, the background colour immediately surrounding the target object causes the colour contrast effect.

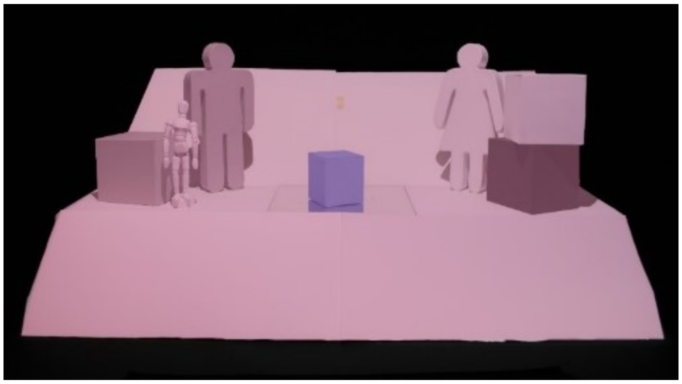

Figure 2. The experimental situation. A projector was used as light source to control background colour (adapting colour) and test stimulus (target colour) separately.

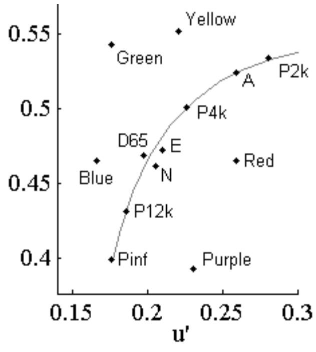

Figure 3. The chromaticities of the backgrounds in u'v' diagram

Five target objects, a neutral grey cube and four familiar objects in European culture (green apple, yellow ripe lemon, red ripe tomato and the blue Smurf) were used in the experiments. The background colour was set at approximately 800 cd/m² at 13 different chromaticities corresponding to: Planckian radiators with correlated colour temperatures (CCT) of 2300K (P2k), 4000K (P4k), 12000K (P12k) and infinite K (Pinf); illuminants A, E and D65, and the most neutral white (N) found by Smet et al. [20] together with five high chroma sources (Red, Yellow, Green, Blue, and Purple). The background colours were calibrated using an OceanOptics QE65Pro tele-spectroradiometer (TSR) on the white (spectrally neutral) background panel and the colorimetric data were calculated using the CIE1964 standard colorimetric observer. Actual measured chromatic values of the 13 backgrounds are shown in Figure 3 and Table 1. Note that the luminance level is very high (760 cd/m²) and the 13 different background chromaticities covered a wide range of chroma values. The high luminance was intended to induce high degrees of adaptation.

Table 1. Measured chromatic values of the testing backgrounds in CIE1976 u'v' diagram

Background	E	D65	A	N	
u'	0.2103	0.1977	0.2590	0.2060	
v'	0.4726	0.4685	0.5237	0.4615	
Background	P2k	P4k	P12k	Pinf	
u'	0.2807	0.2265	0.1861	0.1761	
v'	0.5338	0.5009	0.4316	0.3991	
Background	Yellow	Green	Blue	Purple	Red
u'	0.2209	0.1765	0.1664	0.2307	0.2597
v'	0.5515	0.5426	0.4651	0.3927	0.4655

The observers' task was to adjust the colour appearance of a test stimulus corresponding to a familiar object so that it matched their memory colour or the grey cube appeared achromatic (neutral) by navigating in CIE u'v' space using a keyboard. Observers were also allowed to adjust luminance. Experimental bias due to the starting background was minimized by repeating each match 4 times with 4 different initial target chromaticities with high chroma distributed evenly in hue (,i.e. $+0^{\circ}$, $+90^{\circ}$, $+180^{\circ}$ and $+270^{\circ}$ surrounding the original colour) as target colour. The matched results was measured using the TSR.

Procedure & Observers

Twenty observers took part and they are all the staff and students at KU Leuven passed the Ishihara test with normal colour visions. Each target object was presented to 10 observers (5 males and 5 females) under all 13 background colours. Some observers evaluated more than one target object. For each randomly presented background colour, each observer was asked, after 30-seconds adaptation, to perform the MCM until every background colour was repeated 4 times. After each match, observers gave a 0 to 10 score to evaluate how much he or she feel satisfied with the colour matching results and the match was spectrally recorded using the TSR. In total, 2600 matches were accumulated, i.e. 5 targets x 10 observers x 13 backgrounds x 4 initials).

Result

Observer Variation

Mean Colour Differencefrom the Mean (MCDM) of each target object under each background colour were calculated to represent the observer variation of the result [21]. The CIEDE2000 with zero lightness difference (called DE2000c here) was used in the MCDM calculations. Figure 4 shows the intra- and inter-observer variation in terms of MCDM for each background and each target. The intra observer variation describes the repeatability of the single observer's matching performance among 4 different initial chromaticities while the inter observer variation describe the consistency among all observers of the memory colour or the visually neutral grey. The higher the MCDM, the larger the observer variation, and the lower the repeatability or the consistency. The results showed that Smurf blue colour, a childhood memory colour for most Europeans, achieved the highest repeatability but least consistency among the 5 target objects studied. Also, higher repeatability and consistency performance can also be found for the neutral background than for the colour ones. This implies that objects under a neutral background, close to people's daily life memories, can be matched more consistently by observers. Over all, the MCDM value of 4.76 and 5.56 for the intra- and inter- uncertainties are typical for this type of experiment, considering the original variation of the memory colours [17].

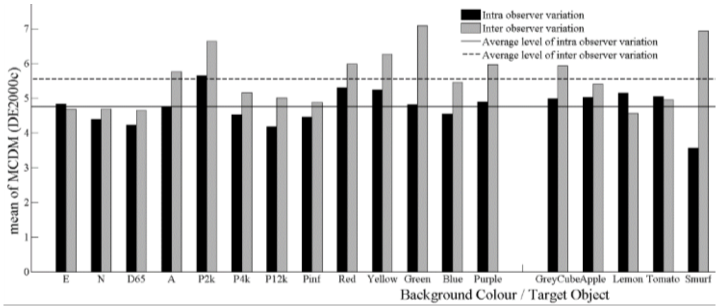

Figure 4. The intra and inter observer variations characterized by MCDM

Performance of CAT02

The average visual chromatic settings for the 13 backgrounds were arranged in 12 pairs of corresponding colours by selecting the data for illuminant E as reference. The formula for the degree of adaptation D in CAT02 as given in equation (1) depends only on the luminance level and the surround condition. Considering the high luminance level of 760cd/m^2 adopted during the experiment, according to equation (1), D is expected to have a value close to 1. The corresponding colour datasets were therefore first used to test CAT02 with D of 1. The performance of the transform was evaluated by calculating the DE2000c values between the CAT02 predictions and the visual result under illuminant E as background colour. Results are illustrated in Figure 5. It was found that CAT02 had a poor performance (mean DE2000c of 11.2), except for some neutral backgrounds. N and D65 had MCDM lower than 2 DE2000c units.

Subsequently, the D was adjusted to a value of 0.28, the same value for all illumination colours resulting in a minimum error of prediction of about 3.7 DE2000c units. The most important part of the modelling is to reduce the error of the adaptation transform for high chroma background colour. A remodeling of the D value based on the chromaticities of the adapting background can meet these need.

The D values were also optimized to achieve minimumDE2000c values for each background/illumination colour for each of the target objects. Figure 6 shows the optimized D values and Figure 5 shows the minimumDE2000c values (1.3 as mean). The result is quite precise with a mean of DE2000c less than 2. This indicates that this set of D value can be used to derive a new CAT model. In Figure 6, two trends can be observed for the optimized D. The first is that the farther the background colour is away from the reference illuminant E (i.e. higher excitation purity), the lower the optimized D will be. This implies that the degree of adaptation is reduced under a higher chroma background (adapting field). The second trend is that observers adapt less to a yellowish background than to a blue one. As is clear from Figure 6, D values are obviously lower when the CCT of the background colours corresponding to Planckian radiators or neutral illuminants is lower than 4000K (P2K and A), than for the ones with CCT higher than 4000K (N, D65, P12k and Pinf). It can be concluded that only depending on the chromaticities of the background colours, D can be modelled to achieve a more accuracy CAT prediction.

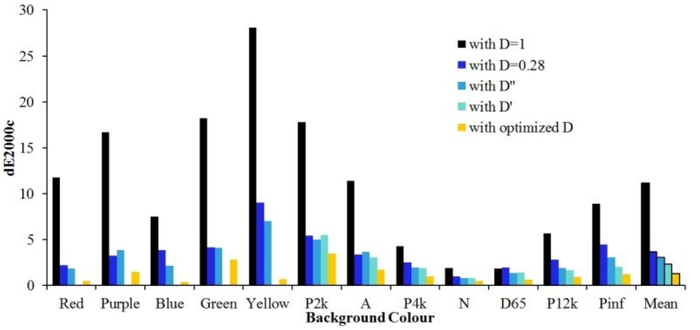

Figure 5. DE2000c values between the CAT02 predictions from background colours to illuminant E and the visual result with illuminant E as background colour.

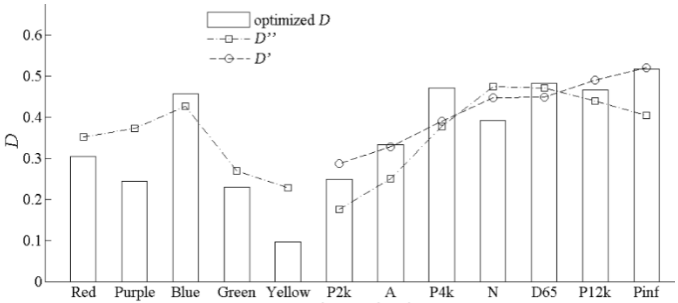

Figure 6. D factor (degree of adaptation) values used in CAT02

Modelling incomplete adaptation according to CCT

The first model, D’, was developed based upon the CCT values of the neutral backgrounds (P2k, P4k, P12k, Pinf, A, D65, N). It is given in equation (2).

$$D' = D_0 \cdot (1 - \frac{T_0}{T}) \tag{2}$$

where D_0 and T_0 are the optimized model parameters; T is the CCT (K) of the background colour. The equation structure is based on the trend that the adaptation to yellower (warmer) appearance of lower CCT sources are less complete.

In equation (2), the constant terms could depend on the original adaptation degree affected by experimental factors such as adapting time, the size of background and the luminance level. The parameter D_0 predicts the D value when the background colour has an infinite CCT.

Using the optimized D values discussed earlier as modelling input, the parameters were trained to be D_0= 0.538 and T_0= 1091 (K). The modelled D values for each background colour are shown in Figure 6 as dashed lines. The r value between this model and the training samples is 0.88. Figure 7 shows the D curve as a function of CCT values. For extremely high CCT backgrounds the degree of adaptation is similar to the neutral background colours. With the D values from this model, DE2000c values between the CAT02 predictions and the visual results are given in Figure 5. The mean error is 2.3 DE2000c units markedly better than that when D=1 and D=0.28. The parameter D_0 shows that the highest adaptation degree in the experiment environment was about 54%, which means a D=0.28 cannot represent the overall adaptation degree of the environment. However a shortcoming of the D’ model is that for extremely high CCT backgrounds, the D factor is larger than the one for reference white as background (illuminance E in the present study with a CCT lower than 6000K). It can also only be used for background or adapting field chromaticities on or close to the blackbody locus.

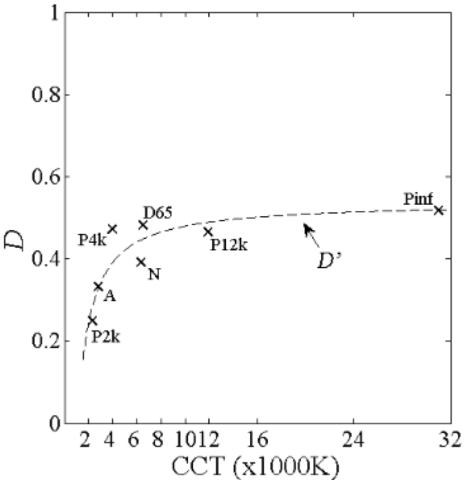

Figure 7. Modelling D’ on CCT values. (‘x’ point: the optimized D)

Modelling incomplete adaptation on background chromaticities

As the D’ model can only predict the background colours along the blackbody locus, a second model, D’’ was then developed that uses the optimized D value of all tested background chromaticities. It can consider a more general condition, especially one where colour contrast also occurs. A polynomial model, given in in equation (3), was developed according to the above two trends (D should be smaller for yellow than for blue and D decreases as chroma increases).

$$D'' = D_0 + p_a \cdot A'_s + p_b \cdot B'_s + p_c \cdot C'_s \tag{3}$$

$$where \quad A'_s = u'_s - u'_0\,,\; B'_s = v'_s - v'_0\,,\; C'_s = \sqrt{{A'_s}^2 + {B'_s}^2};$$

and D_0, p_a, p_b and p_c are the optimized model parameters; u'_s and v'_s is the chromaticity of the background colour in the u’v’ chromaticity diagram; u'_0 and v'_0 is the chromaticity of a neutral colour center (NCC), which in this case is illuminant E; A'_s and B'_s are the relative chromaticity of the background colour to the NCC; C'_s is the u’v’ distance from the NCC to background colour, expressed as chroma. In equation (3), the constant terms could depend on the original adaptation degree affected by experimental factors such as adapting time, the size of background and the luminance level. The parameter D_0 predicts the D value when the NCC is the background colour. The second and the third terms reflect the trend that observers adapt less to yellowish backgrounds/illuminations than to blueish ones, while the last term describes the trend of lower D with higher chroma.

Using the optimized D values as modeling input, the parameters were trained to be D_0= 0.487, p_a= -0.655, p_b= -0.992 and p_c= -2.19. The modelled D values for each background colour are shown in Figure 6 as dots and solid lines. The r value between this model and the training samples is 0.76. With the D values from the model, DE2000c values between the CAT02 predictions and the visual result are given in Figure 5. The model performed slightly better for neutral background colours than for those with yellowish and purplish colours. The mean error is 3.1 DE2000c units, which far lower than those found for D=1 (11.2 units) and slightly lower than for D=0.28 (3.7 units). The parameter D_0 shows that the highest adaptation degree is 49%. One of the potential shortcoming of the D” model is an underestimation for yellow and red backgrounds and an over prediction for blue backgrounds. This may be caused by the sparse sampling of background colours. Further experimental data are therefore needed.

Discussion

T0 and NCC in the models

When $T = T_0$, the D value in the D’ model is zero. That is to say the T_0 value (1091K in the present experiment) is the lower limit of the CCT that observers can ever adapt to. Note that chromaticity values corresponding to extremely low CCT (< 2000K) are actually high chroma colours where colour contrast effects potentially become important. The D’ model may not be used when $T < 2000$K.

The NCC in the D’’ model is free to choose and it is not mandatory to make the NCC the same as the reference white. Where is the best NCC? The issue of the achromatic point studied by many other researchers [20, 22] and needs further discussion. According to the structure of the D” model, the most important criteria for NCC is that it should achieve the highest D comparing with any other background colour. In the D’’ model, the parameter

D_0 is the D value defined by the chromaticity of the NCC. It is independent of the colour contrast effect because the model transforms the target colours under all background colours to the NCC background. However, in the D' model, the parameter D_0predictsthe D value when the background colour has an infinite high CCT. In consideration of the D'' model's over prediction in the blue, more testing data is required to determine whether NCC should be chosen at a blue chromaticity rather than a neutral one.

Luminance level

The luminance in the present experiment is approximately 800cd/m2, which is a very high level aimed to fully adapt observers to the illumination colour However, both optimized D data and the above models show that the degree of adaptation is only around 50% for the neutral backgrounds. This value challenges the D factor formula in CAT02 as equation (1). One explanation is that the adapting time in the present experiment (30s~60s) is not enough for the observers to conduct a full adaptation or that the observers require a more immersive environment to more fully adapt. It is typical to find that incomplete adaptation occurs much more in the experiment than in the real-life [23].

Target dependent correction

The present experiment tested 5 target objects having different colours. Figure 8 shows the errors for the CAT02 transform in terms of DE2000c (from 12 background colours to illuminance E) with the optimized Ds (to minimize mean DE2000c for each target on each background) for each colour target object. It can be seen that the green apple data can be well predicted under a red background but not a green one; the lemon data shows the largest error under yellow or orange backgrounds; for the tomato, CAT02 works markedly better with green background than red. These trends indicate that the smaller the difference between the target colour and the background colour, the larger error the CAT will be. The increased error for similar target – background colours indicates that simultaneous contrast could be affecting the colour appearance of the target objects thereby reducing the performance of the CAT. A correction depending on the colour differences between targets and backgrounds, accounting for colour contrast effects [14], would therefore be desirable to further improve colour appearance prediction under different viewing conditions.

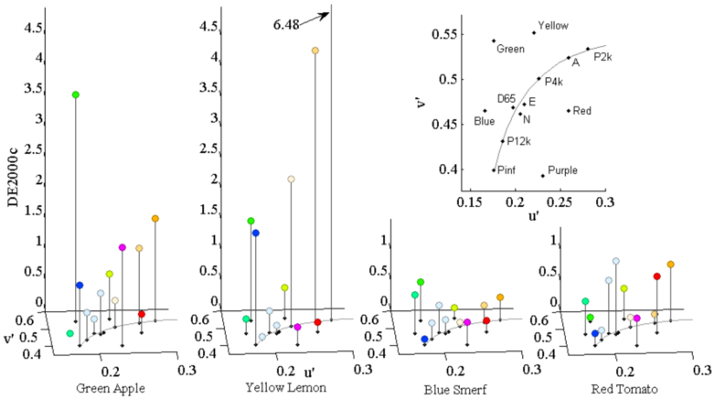

Figure 8. Errors of CAT02 (from 12 background colours to illuminance E) in terms of DE2000c with the optimized Ds (to minimize mean DE2000c for each target on each background)

Conclusion

An experiment using memory colour matching approach in real scene at a high luminance level, was conducted. 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 high chroma. Two kinds of model for the D factor in CAT02 were developed, one as a function of CCT and one as a function of the u'v' chromaticity of background colours. The performance of CAT02 was also found to be possibly negatively affected by colour contrast effects when target objects and background colours are similar in colour. However, further study is required.

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References

[1] von Kries, J. (1902). Chromatic adaptation. Festschrift der Albrecht-Ludwigs-Universität, 145-158.

[2] Luo, M. R. and Hunt, R. W. G. (1998). A chromatic adaptation transform and a colour inconstancy index. Color Research & Application, 23(3), 154-158.

[3] Luo, M. R. (2000). A review of chromatic adaptation transforms. Review of Progress in Coloration and Related Topics, 30(1), 77-92.

[4] CIE160/159-2004, 2004

[5] Moroney, N., Fairchild, M. D., Hunt, R. W., Li, C., Luo, M. R. and Newman, T. (2002, January). The CIECAM02 color appearance model. In Color and Imaging Conference (Vol. 2002, No. 1, pp. 23-27). Society for Imaging Science and Technology.

[6] Fairchild, M. D. and Reniff, L. (1995). Time course of chromatic adaptation for color-appearance judgments. JOSA A, 12(5), 824-833.

[7] Luo, M. R., Gao, X. W. and Scrivener, S. A. R. (1995). Quantifying colour appearance. Part V. Simultaneous contrast. Color Res. & App., 20(1), 18-28.

[8] Whittle, P. (2003). Contrast colours. Colour perception: Mind and the physical world, 115-138.

[9] Wu, R. C. and Wardman, R. H. (2007). Proposed modification to the CIECAM02 colour appearance model to include the simultaneous contrast effects. Color Res. & App., 32(2), 121-129.

[10] Luo, M. R., & Hunt, R. W. G. (1998). The structure of the CIE 1997 colour appearance model (CIECAM97s). Color Res. & App., 23(3), 138-146.

[11] Lawrence, A and Reeves, A. Simultaneous Color Constancy. JOSA a-Optics Image Science and Vision. 1986 Oct; 3(10):1743-1751.

[12] Lawrence, A and Goldstein, R. Simultaneous Color Constancy, lightness, and Brightness. JOSA a-Optics Image Science and Vision. 1987Dec; 4(12):2281-2285

[13] Ekroll, V. and Faul, F. (2012). New laws of simultaneous contrast? Seeing and perceiving, 25(2), 107-141.

[14] Ekroll, V. and Faul, F. (2012). Basic characteristics of simultaneous color contrast revisited. Psychological science, 0956797612443369.

[15] Allred, S. R., and Olkkonen, M. (2013). The effect of background and illumination on color identification of real, 3D objects. Frontiers in psychology, 4.

[16] Smet, K. A. G., Zhai, Q, Luo, M.R. and Hanselaer, P. Investigating Chromatic Adaptation Using Memory Colours, *4th CIE Expert Symposium on Colour and Visual Appearance*, Sept, 2016, Prague

[17] Smet, K., Ryckaert, W. R., Pointer, M. R., Deconinck, G. and Hanselaer, P. (2011). Colour appearance rating of familiar real objects. Color Research & Application, 36(3), 192-200.

[18] Smet, K., Ryckaert, W., Pointer, M., Deconinck, G. and Hanselaer, P. (2012). A Memory Colour Quality Metric for White Light Sources. Energy and Buildings, 49 (June), art.nr.10.1016/j.enbuild.2012.02.008, 216-225.

[19] Smet, K. and Hanselaer, P. (2015). Memory and preferred colours and the colour rendition evaluation of white light sources. Lighting Research and Technology, art.nr. 10.1177/1477153514568584.

[20] Smet, K. A. G., Deconinck, G. and Hanselaer, P. (2014). Chromaticity of unique white in object mode. Optics Express, 22(21), 25830-25841.

[21] Billmeyer, F. W., and Alessi, P. Assesment of color measuring instruments, Color Res and Appl., 1981, 6(4): 195-202.

[22] Kuriki, I. (2006). The loci of achromatic points in a real environment under various illuminant chromaticities. Vision research, 46(19), 3055-3066.

[23] Foster, D. H. (2011). Color constancy. Vision research, 51(7), 674-700.

Author Biography

Qiyan Zhai received his BS in engineering from Zhejiang University (2013) and has been a PhD candidate supervised by professor M.R.Luo in Zhejiang University since 2013. Mr. Zhai was an international scholar in KU Leuven, Belgium in 2015. His work has focused on colour appearance model and LED lighting quality.