A Study of Neutral White and Degree of Chromatic Adaptation

Qiyan Zhai [1], *Ming Ronnier Luo** [1,2]

[1] *State Key Laboratory of Modern Optical Instrumentation, Zhejiang University, Hangzhou, China*
[2] *School of Design, Leeds University, Leeds, UK*

**Corresponding Author: M.R.Luo@zju.edu.cn*

Abstract

An investigation was carried out to study the neutral white of chromatic adaptation in colour science. The experiment was conducted for matching neutral whites under different white illuminants using both surface and self-luminous colours to collect data of the neutral whites of human vison under different illuminants (adaptation fields). The result proves the previous study about the chromatic adaptation. Not all the white illuminants are found neutral even the adaptation time is long enough. The baseline illuminant of the 2-step CAT was found as the illuminant with the same chromaticity of the neutral white under it. The results were also used to test models of the effective degree of chromatic adaptation, which was found highly associated with the viewing media in the present study.

Introduction

Chromatic adaptation (CA) is an important function in human colour vision. Chromatic adaptation transform (CAT) is used to describe this effect by predicting *corresponding colours* [1], for which a pair of colour stimuli (normally presented in XYZ values) showing same colour appearance under two different illuminants. CAT02 [2] is the most widely used. The concept of CA has been that one will report a perfect white object under an illuminant of given corrected colour temperature (CCT) to be neutral after full adaptation. Note that the chromaticity of an illuminant is defined as the colour of a perfect white object having unity spectral reflectance. However, our previous study [3-5] showed that the CAT02 over-predict the effect of CA, i.e. the experimental result showed an under-prediction of *degree of adaptation* (D) [6] at CAT02. The modified D function, called the *effective degree of adaptation* (D_{eff}), was developed according to the chromaticity of illuminant. It was found that the more colourful the illuminant is, the less the observer will adapt to it (lower D_{eff}); But the D_{eff} falls less rapidly along the daylight locus and towards the blue direction. This model indicates that some lower CCT illuminants cannot achieve the full adaptation. For example, the effective D value of the CIE illuminant A is lower than that of the CIE illuminant D65 in the previous experiment [3, 4]. Therefore, the perfect white object under illuminant A will always appear to be yellowish rather than neutral, regardless the adaptation time (Figure 1). In other words, not all the white light sources are perceived a neutral colour appearance. This inference seems to disagree the concept of reference white, discounting illuminant. Note that our previous study collected the data using a projected light to adjust memory colours in an immersive environment at a high luminance level (800 cd/m^2). The present experiment was designed to verify the previous results using a completely different setup at a much lower luminance level using both surface and self-luminous colours.

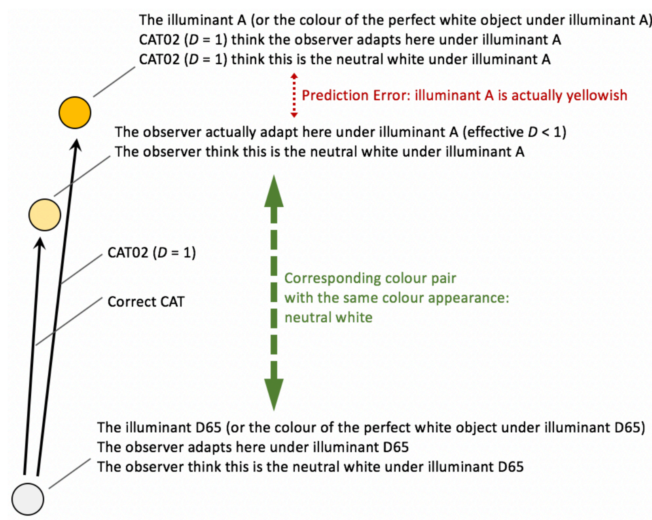

Figure 1. *An explanation of the relationship between chromatic adaptation and neutral whites. Even the observer recognizes D65 to be neutral, s/he will find illuminant A to be yellowish rather than neutral due to the low degree of adaptation.*

Furthermore, our previous study [4] proposed a 2-step CAT to replace the present 1-step CAT in order to clearly define D. A 2-step CAT involves an illuminant representing the baseline states between the test and reference illuminants for the calculation. In the first step the test colour is transformed from test illuminant to the baseline illuminant, and it is then transformed to the reference illuminant. Degrees of adaptation of any other illuminants should be calculated relative to the baseline illuminant. Therefore, this illuminant is expected to produce a neutral adaptation field according to the concept of CA. That is, the chromaticity of neural white under the baseline illuminant is equal to the chromaticity of the baseline illuminant.

The neutral white is also a very important issue for lighting, image and surface colour industries. The experiments searching neutral white light sources have had continued during last century. However, their results varied in a vary large CCT range from 4000K to 15000K on or below the black body locus (*BBL*). More recent studies investigated the so called neutral or natural white locus. It was found that the perceived whites were not located at blackbody locus (*BBL*) [7-10]. Smet *et al*. [11, 12] studied the neutral white (unique white) in both object mode and illuminant mode and found that the neutral white is located below the *BBL* with a Duv value (distance to *BBL* on CIE 1960 uv diagram) of -0.0085 around 6000K.

This paper will introduce an experiment for matching neutral colours under a very large range of white illuminants (3000K < CCT < 16000K, -0.03 < Duv < 0.02) using both surface and self-luminous colours. The aims are (1) to collect data of neutral white under different illuminants, (2) to explore the most adaptable illuminant around the black body locus as the baseline illuminant of the 2-step CAT and (3) to obtain D_{eff} values around the black body locus for modelling.

Experiments

Illuminants and the adaptation field.

The experiment was conducted in a viewing cabinet equipped with a spectrum tuneable LED illumination system *'LEDcube'* produced by *ThousLite* Inc., China. The inner wall of the cabinet was painted as having L^* of 80 in CIELAB. In total, 58 illuminants were used in the experiment (see Figure 1a), i.e. 9 CCTs (3000K, 3500K, 4000K, 4500K, 5000K, 6000K, 6500K, 10000K and 15000K) and 7 Duv levels (-0.025, -0.0175, -0.0125, -0.0075, 0, 0.0075 and 0.015). The luminance was set at 270cd/m^2. All the illuminants were intended to have high colour rendering property, i.e. set CIE-R_a values over 90. The experiment was divided into two parts: using surface and self-luminous colours separately. In the experiment, the observers had viewing angles of 70^o and 3^o for the adapting and target fields, respectively.

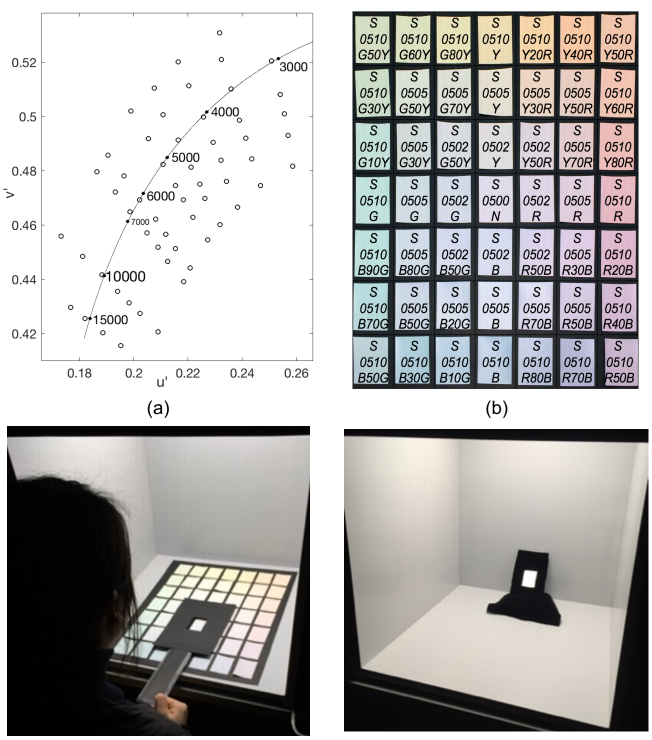

Figure 2. *Experiment setting. (a) The illuminant used in the experiment plotted in CIE 1976 u'v' space; (b) The NCS samples used in the experiment part 1; (c) The experiment situation of part 1; (d) The experiment situation of part 2;*

Part 1: surface colour

The NCS (*Natural Colour System*) colour patches from the *Scandinavian Colour Institute*, Sweden, were used as target colours here. Forty-nigh different patches near the neutral area were selected and arranged as a seven by seven array according to NCS hue (red on the right, yellow on the up, green on the left, and blue on the down) and chroma (neutral on the centre and high chroma around outside) direction, shown in Figure 2b. The selected patches had NCS blackness of 5, and NCS chromaticness values of 0, 2, 5 and 10. Note that the hue direction of this colour array is also similar to the CIELAB or CAM02-UCS. The colour patches array was place on the bottom of the cabinet and illuminated by the test illuminant. The observers used a black mask to cover the neighbouring patches when s/he observes a patch to avoid background effect (Figure 2c).

Each observer was first asked adapt to a randomly selected test illuminants for one minute which could achieve 90% adaptation [13, 14]. After the adaptation, observers were instructed to identify a colour on the colour patches array appeared most neutral (defined as no trace of hue). In the experiment, observers were instructed to start from the centre patch (S-0500-N) and judged its colour composition, e.g. red. Then moved to the opposite direction, e.g. green (left), to a neighbouring patch, and repeat the process until achieving a patch with no perception of hue. Observers were then asked to verify the final decision by viewing all the neighbouring colours before reporting the result. The same procedure will go through all the test illuminants. Twelves observers with normal colour vision participated the experiment. Each colour patch was measured by a *Jeti* tele-spectroradiometer (TSR) in terms of reflectance against a PTFE tile. The chromaticity was calculated by multiplying the SPD of the illuminant and CIE 1964 colour matching function.

Part 2: self-luminous colour

In this part, a calibrated mobile phone display was used. The luminance of the colour showed on the display was constantly control at 300 cd/m^2. The display was covered using a black mask having the same size as part 1 (see Figure 2d) to make the viewing size constant in the whole experiment. After 1-minute adaptation under a random illuminant, observers used a keyboard to control the colour shown on the display. They navigated CIELAB a^* and b^* controls with constant lightness to find the neutral white. It is similar to our previous experiment and also the method of Chauhan *et al.* [15]. The starting chromaticity under each illuminant was set equal to the chromaticity of that illuminant. The final answers under each illuminant were measured by the TSR. Twelves observers with normal colour vision participated in the experiment. Note that the observers were asked to match the neutral white in their memory without considering the departure from neutral of the background.

Results & Discussion

Neutral whites and the baseline illuminant

The results are plotted in u'v' chromaticity diagram as shown in Figure 3. The open circles and red points are the chromaticity of the test illuminants and visual results, respectively. Each vector means a colour shift. The vector having no colour shift represents the most neutral illuminant or the baseline illuminant.

For the surface colours, Figure 3a shows a consistent pattern, i.e. all vectors converge to a single point close to 6000K at *BBL*. It indicates that the neutral white is located around 6000K at *BBL*.

However, the convergent chromaticities of individual observers vary in a rather large range from 4500K to 6500K.

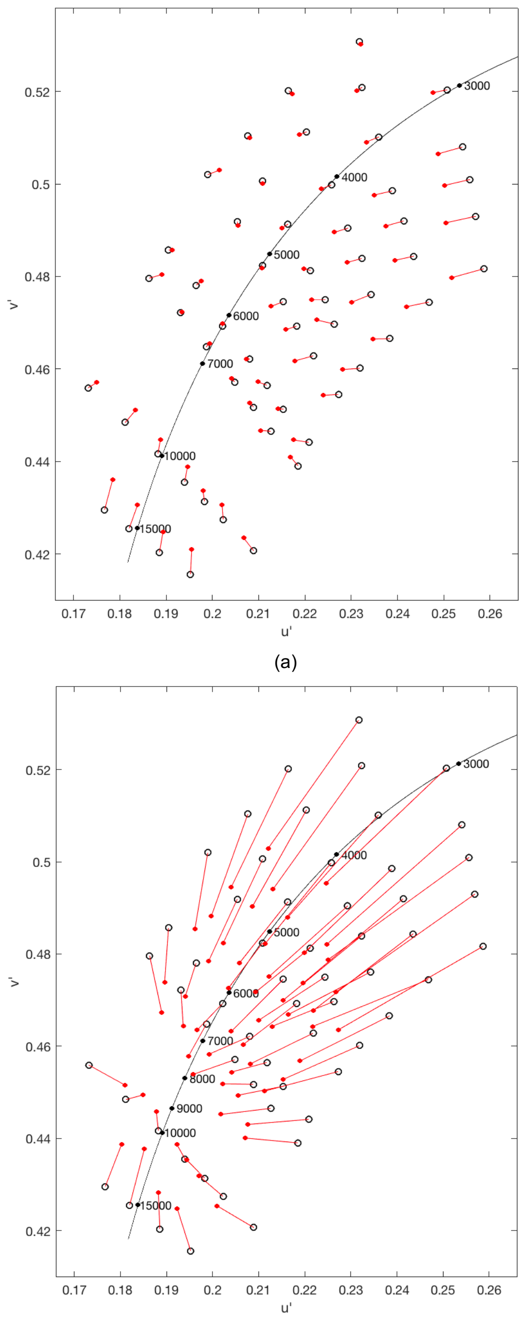

Figure 3. *Neutral white under each illuminant plotted on CIE 1976 u'v' diagram: (a) surface colours results from the experiment part 1; (b) self-luminous colours results from the experiment part 2. The open and filled circles are the chromaticity of the test illuminants and visual results, respectively.*

For the self-luminous colours, Figure 3b shows that the effect of neutral whites having a much larger colour shift than those of the surface colours. The neutral whites below 3000K illuminants had a perceived neutral colour as high as 4500K. The spread of convergent chromaticity spreads between 6500K and 10000K at *BBL*, while the individual observer results greatly vary from 6000K to about 12000K. The results showed a media effect, i.e. the neutral white of self-luminous colours had a much higher CCT then that of surface colours.

Another difference between the two media is that the neutral white results of the surface colours above the *BBL* are located close to the chromaticity of the illuminants, while those of self-luminous colours had large shift. One possible reason for this is that the gamut size of those illuminants were smaller than that of illuminants below *BBL*. The NCS patches array under those illuminants had a rather smaller colour gamut for observers to search. In summary, 6000K and 9000K, having zero Duv, found to be the convergent chromaticity, or approximate baseline illuminant for the surface and monitor colours respectively.

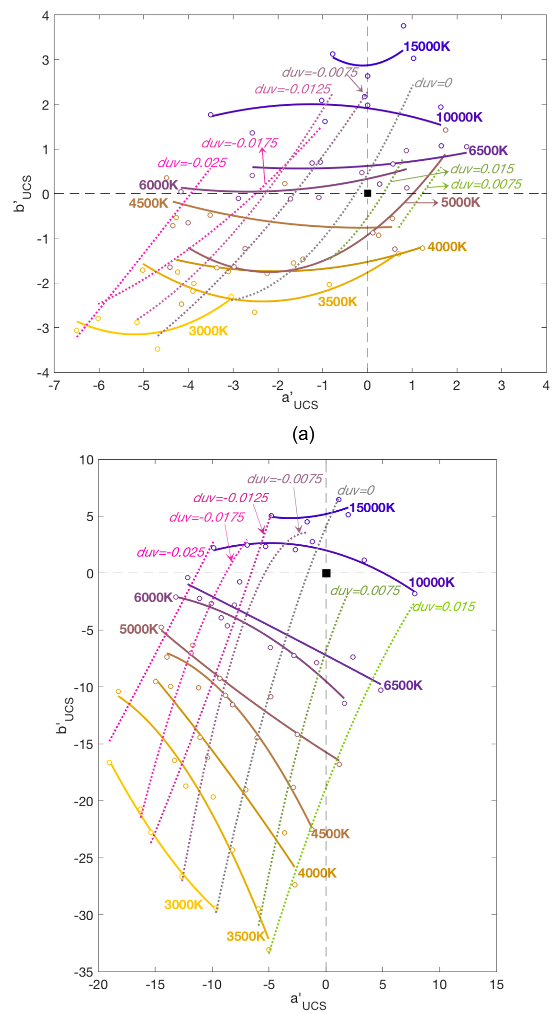

Figure 4. *Neutral white under each illuminant transformed into CAM02-UCS with D=1: (a) surface colours results from the experiment part 1; (b) self-luminous colours results from the experiment part 2. The solid curves were fitted the neutral whites under illuminants of having CCT levels. The dashed lines are fitted to the neutral whites under illuminants having same Duv levels.*

In consideration of the poor uniformity of CIE 1976 u'v' diagram and no chromatic adaptation, the neutral white under each illuminant was transformed to the CAM02-UCS for which CAT02 is embedded with D of 1. These are plotted in Figure 4, where the solid curves were fitted the neutral whites under illuminants of same CCT level. The dashed lines are fitted to the neutral whites under illuminants having same Duv levels. According to the concept of CA, all the neutral whites are expected to be at the test illuminant, origin of CAM02-UCS. The distance between these two chromaticity indicates the error of prediction by the CAT, which is most likely to be caused by the over-prediction of D values. It can also be seen that the range of axes in Figure 4b is much larger than that in Figure 4a. This implies that global D_{eff} of the self-luminous colours are much lower than those of the surface colours.

In Figure 4a, the coordinate origin was located between the CCT fitting lines of 5000K and 6000K biased toward 6000K, and between the Duv fitting lines of 0 and 0.0075 biased toward 0. In Figure 4b, the origin was located between 6500K and 10000K biased toward 10000K, and between the Duv of 0 and 0.0075 biased toward 0. Note that the baseline illuminant is expected to have zero error with D_{eff} = 1. The figures indicate that surface and self-luminous colours have baseline illuminants about 6000K at *BBL* and about 9000K at *BBL*, respectively. With better uniformity of CAM02-UCS, these values agree with those obtained on the CIE 1976 u'v' diagram above.

The model of effective degree of adaptation

Note that D_{eff} values cannot be obtained from Figure 3 or Figure 4. Neither a longer length of the vector in Figure 3 nor a farer distance away from the coordinate origin in Figure 4 refers to a lower D_{eff}. They both refer to the absolute error. A higher ratio of the absolute error divided by the colour difference between a test illuminant and the baseline illuminant refers to a lower D_{eff}. Therefore, D_{eff} can be simply derived as following.

Assuming that the neutral white was expertly with same chromaticity of the illuminant under the baseline illuminant found above, all the neutral white results are transformed to this baseline illuminant via the CAT02. D_{eff} value under each illuminant was optimised to minimise the prediction errors of the CAT02 in terms of chromatic difference of CIEDE2000 (set lightness difference to zero). Two models, Equations (1) and (2), were developed to fit the D_{eff} values as a function of CCT and Duv values.

$$D_{eff} = D_0 \cdot \left(1 - \frac{T_0}{T}\right) \tag{1}$$

$$D_{eff} = p_1 + p_2 \cdot d + p_3 \cdot d^2 \tag{2}$$

where T and d are the CCT and Duv values of the illuminants in question, while D_0, T_0, p_1, p_2 *and* p_3 are the optimized coefficients. The effective degrees of adaptation and the fitted models are plotted in Figure 5 together with the function of D_{eff} model obtained in our earlier study [3] with the same form as Equation (1).

In Figure 5, the effect found in our previous study (the lower the CCT, the lower the D_{eff})[3] was not obvious for the surface colour under the viewing condition of the present experiment. The adaptation is stable for the surface colours over CCT, while the function on display colours (D_0 = 0.709, T_0 = 814K) is quite similar to our previous curve (D_0 = 0.538, T_0 = 1091K) [3]. Higher order polynomials had also been developed to fit the present data while the Equations (1) still performed the best. This implies that the highest D_{eff} values could have an infinitely high CCT. More data are needed to verify the model.

For Duv, it can be seen that it is more or less stable for the surface colours before reaching zero, and then slightly increase for positive Duv values (possible same reason about the small gamut of greenish illuminants). Again, there is another effect for the display colours, i.e. adaptation is the greater from negative (purplish white) to positive (greenish whites) Duv values. The D_{eff} values of illuminants with negative Duv values are even higher than those of the baseline illuminant.

Note that, in the present modelling, only the illuminants around the black body locus were covered. When the data combined with coloured illuminants in the future work, D_{eff} models based on the tristimulus values or chromaticity values such as CIE1976 u'v' values should be considered rather than CCT and Duv, for more simple calculations in industry applications.

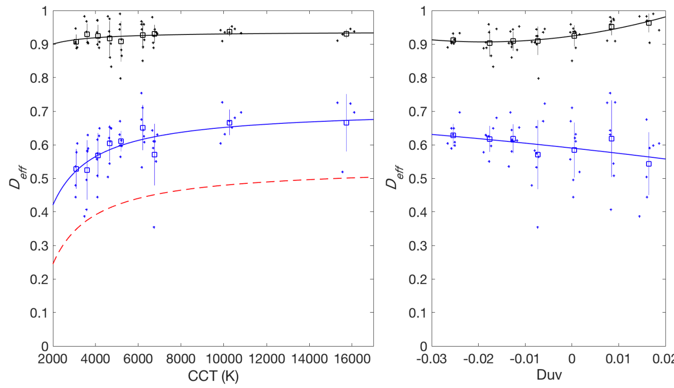

Figure 5. *The effective Degrees of adaptation and the fitted Equation (1) (based on CCT) and Equation (2) (based on both CCT and Duv). The black and blue curves/points are for the surface colours and the self-luminous colours in the present experiment, respectively. The red dashed line is the model in our previous study.*

Does the baseline illuminant have the highest effective degree of adaptation?

According to the definition of the baseline illuminant above, when an observer having no adaptation to a certain illuminant, observers' adapting chromaticity will equal to the baseline illuminant (they will consider that the chromaticity of the baseline illuminant is the neutral white). However, it does not guarantee the baseline illuminant to have the highest D_{eff} value. The above fitted functions also confirmed this. An example was plotted as Figure 6.

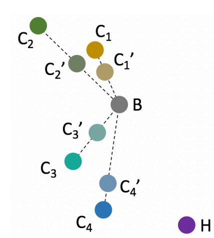

Figure 6. *On a chromaticity plane, point B is the baseline illuminant while point H is the illuminant with the highest D_{eff} value. C1, C2, C3 and C4 are four illuminants while C1', C2', C3' and C4' are the visual adapted points of them.*

In Figure 6, point B is the baseline illuminant while point H is the illuminant with the highest D_{eff} value on a chromaticity plane. C_1, C_2, C_3 and C_4 are four coloured illuminants while C_1', C_2', C_3' and C_4' are the visual adapted points of these illuminants. Because $HC_1 < HC_2$, the D_{eff} value of C_1 is higher than that of C_2. Therefore, $BC_1'/BC_1 > BC_2'/BC_2$. Because $HC_4 < HC_3$, the D_{eff} value of C_4 is higher than C_3. Therefore, $BC_4'/BC_4 > BC_3'/BC_3$. However, B, C_n and C_n' (n=1, 2, 3 or 4) are always on the same line based on the definition of the baseline illuminant. In an extreme situation when C_1 and C_2 are close enough, $BC_2' \leq BC_1'$ and $BC_2 \geq BC_1$ will be both true at the same time. This implies that a more colourful illuminant could be adapted less colourful. To avoid this problem in the future work, the D_{eff} model should be limited in mathematics to ensure that BC_n' increase monotonously when BC_n increase.

Conclusion

The data of neutral whites under different illuminants was achieved for both the surface and display colours. The baseline illuminants of the 2-step CAT was found with different CCTs for the surface colours (6000K) and self-luminous colours (9000K) respectively, at BBL. Models of effective degree of chromatic adaptation were investigated and compared with that found in the previous study. Overall, it can be concluded that the degree of adaptation is highly associated with the media, i.e. surface, display and projected colours. The baseline illuminant has not to be the illuminant with the highest effective degree of adaptation.

References

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

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

[3] Q. Zhai, M. R. Luo, P. Hanselaer, and K. A. G. Smet, "Modelling Incomplete Chromatic Adaptation and Colour Contrast Using Memory Colours," in *IS&T* 24th *Color Imaging Conference* (San Diego, US, 2016), p. 82.

[4] K. A. G. Smet, Q. Zhai, M. R. Luo, and P. Hanselaer, "The study of chromatic adaptation using memory colors. Part I: Neutral Illuminants," *Optics Express* (under review) (2017).

[5] K. A. G. Smet, Q. Zhai, M. R. Luo, and P. Hanselaer, "The study of chromatic adaptation using memory colors. Part II: Colored Illuminants," *Optics Express* (under review) (2017).

[6] N. Moroney, M. D. Fairchild, R. W. G. Hunt, C. Li, M. R. Luo, and T. Newman, "The CIECAM02 color appearance model," in *IS&T/SID 10th Color Imaging Conference,* (2002), p. 23.

[7] M. S. Rea and J. P. Freyssinier, “White lighting,” *Color Res. Appl.* 38(2), 82–92 (2013).

[8] H. Li, M. R. Luo, X. Y Liu, B. Y. Wang and H. Y. Liu, "Evaluation of colour appearance in a real lit room", *Light. Res and Tech.*, 48, 412-432 (2016).

[9] Q Wang, H Xu, and J Cai, "Chromaticity of white sensation for LED lighting," *Chinese Optics Letters* 13(7), 073301, (2015).

[10] Y. Ohno and M. Fein, “Vision experiment on white light chromaticity for lighting,” in *CIE/USA-CNC/CIE Biennial Joint Meeting* (Davis, USA, 2013).

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

[12] K. A. G. Smet, G. Deconinck, and P. Hanselaer, "Chromaticity of unique white in illumination mode," *Optics express* 23(10), 12488-12495 (2015).

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

[14] O. Rinner, and K. R. Gegenfurtner, "Time course of chromatic adaptation for color appearance and discrimination," *Vision research* 40(14), 1813-1826 (2000).

[15] T. Chauhan, et al, "The achromatic locus: effect of navigation direction in color space," *Journal of vision* 14(1), 25-25 (2014).

Author Biography

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