https://doi.org/10.2352/issn.2169-2629.2019.27.34

Proposed modification to the CAM16 colour appearance model to predict the simultaneous colour contrast effect

Yuechen Zhu[1] and 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

Experiments were carried out to investigate the simultaneous colour contrast effect on a self-luminous display using colour matching method. The goals of this study were to accumulate a new visual dataset and to extend CAM16 to predict the simultaneous colour contrast effect. Five coloured targets together with a neutral grey were studied. A total of 132 test/background combinations were displayed on a calibrated display. Twenty normal colour vision observers performed colour matching in the experiment. In total, 2,640 matches were accumulated. The data were used to accurately model the lightness and hue contrast results. The model was also successfully tested using two independent datasets.

Introduction

A colour appearance model (CAM) is a mathematical model that is used to predict the perceptual aspects of human colour vision under various viewing conditions, i.e., the appearance of a colour does not in accord with the corresponding physical measurement of the stimulus source [1]. Various colour appearance phenomena, such as chromatic adaptation, luminance range effect, Hunt effect, Stevens effect, Helmholtz-Kohlrausch Effect, and simultaneous contrast effect can be predicted by a colour appearance model [2]. Colour appearance phenomena are related to human perception and the mechanism is complex. Various colour appearance models have been developed. However, the common visual phenomenon, simultaneous colour contrast, has not been considered, in which the appearance of a colour is affected by the surrounding colour. Previous investigations have shown that the appearance of colour considered moves toward the opposite colour of the surrounding colours, following the opponent colour theory [3-4]. And the effect is usually studied in a centre-surround paradigm, also called test/background paradigm [4-6]. The phenomena are illustrated in Figure 1, (a) lightness contrast, a darker background induces a colour to appear lighter; (b) hue contrast, a red background induces a colour to appear bluish; (c) colourfulness contrast, a colourless background induces a colour to appear more colourful. The colours of the ('X') in each diagram are the same. The pattern in the shape of the double crosses in Figure 1 was also used in the present experiment.

This effect was modelled in Hunt94 [7-9] colour appearance model, which was the first relatively comprehensive colour appearance model. It predicts a wide range of visual phenomena, including the simultaneous contrast effect to some extent. However, the model did not predict well to the visual results because chromatic contrast has not been taken into consideration. Until 1997, CIE first recommended CIECAM97s [10]. This was superseded by CIECAM02 [11] and it has been widely used. More recently, a new CIE technical committee JTC10 was formed to recommend the recently published CAM16 [12].

Most of the colour appearance phenomena are predicted by CAM16. However, the prediction for the simultaneous contrast effect is not satisfactory because of the poor predictions provided by the Hunt model. For example, the model gave a poor predictive performance for Wang *et al.*'s dataset [13-15]. This paper describes a psychophysical experiment to accumulate a new visual dataset, which can be used to extend CAM16 to predict the simultaneous colour contrast effect.

(a)

(b)

(c)

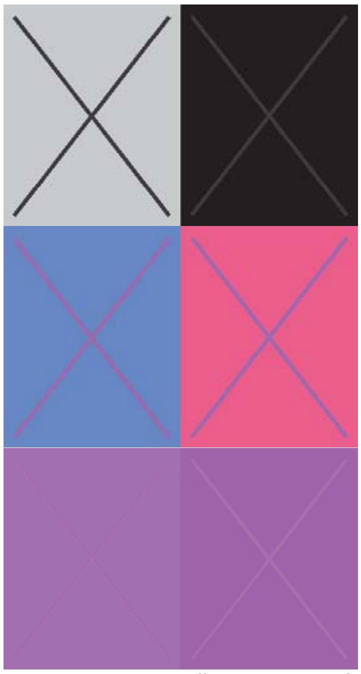

Figure 1. *Simultaneous colour contrast effect, the colours of the crosses in each diagram are the same. (a) lightness contrast; (b) hue contrast; (c) colourfulness contrast.*

Experimental

The experiment was conducted on an EIZO-CG243W display (size: 24.1", luminous level: 125 cd/m^2) in a darkened room. The display passed various tests. Typically, it had a uniformity of 0.91 ΔE^*_{ab} between the middle and the other 8 surrounding regions on the display. It was characterized using a GOG model, which gave a mean ΔE^*_{ab} of 0.72 to predict the 24 colours on X-rite 24 ColorChecker target.

Observers sat at a distance of 80 cm away from the monitor. They were asked to adapt in a darkened room for 1 min viewing a grey background (CCT: 6500K, luminance level: 23 cd/m^2, L^*: 50) on the display. A double crosses image (see Figure 1) was presented on the display and the observers then adjusted the lightness, chroma and hue of the test cross on the right via a keyboard in CIELAB colour space to match the colour of the reference cross on the left until they looked the same. Once the observer confirmed the well-matched colour, the next randomly generated combination was presented, and so on. The background on the left was fixed (CCT: 6500K, luminance level: 23 cd/m^2, L^*: 50), and the colour of the background on the right changed.

The experiment was divided into two parts to investigate the lightness contrast and hue contrast respectively. Figure 2 shows the experiment setting. Figure 2a shows experimental situation, Figure 2b shows operational interface of lightness contrast experiment designed via Matlab GUI, Figure 2c shows operational interface of hue contrast experiment designed via Matlab GUI.

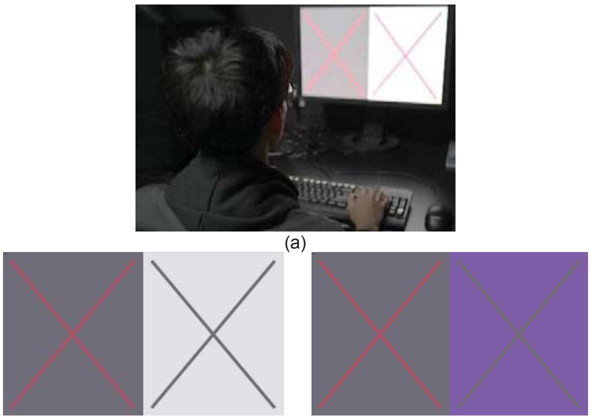

Figure 2. *Experimental setting. (a) Experimental situation; (b) Operational interface of lightness contrast experiment; (c) Operational interface of hue contrast experiment.*

Six target colours (Red, Yellow, Green, Blue, Magenta, Neutral grey) were selected considering the colour distribution in hue circle. The L^*, C^*_{ab}, h^*_{ab} and L (cd/m^2) values of the target colours are given in Table 1. Figure 3 shows the coordinates of target colours in CIELAB a^*b^* plane. It can be seen in Figure 2 that the reference combination on the left always has a mid-grey background.

Table 1. The CIELAB coordinates for the 6 target colours.

Target colour	L^*	C^*_{ab}	h^*_{ab}	L (cd/m^2)
Red	50.0	30.0	7.4	23.1
Yellow	50.0	30.0	79.9	23.1
Green	50.0	30.0	139.5	23.1
Blue	50.0	30.0	236.4	23.1
Magenta	50.0	30.0	301.9	23.1
Neutral grey	70.0	3.0	293.9	23.1

For studying the lightness contrast effect, six series of colours Red, Yellow, Green, Blue, Magenta, Neutral grey were prepared for matching. The test 'X' of each coloured target 'X' (Red, Yellow, Green, Blue, Magenta) was against seven grey backgrounds differed in lightness (L^* of 0, 20, 40, 50, 60, 80, 100). While test 'X' of neutral grey was against eleven grey backgrounds differed in lightness (L^* of 0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100). Table 2 shows the CIELAB values of the backgrounds in the six hue series.

This results in a total of 46 combinations for each observer, i.e., 5 targets x 7 backgrounds + 1 grey target x 11 backgrounds.

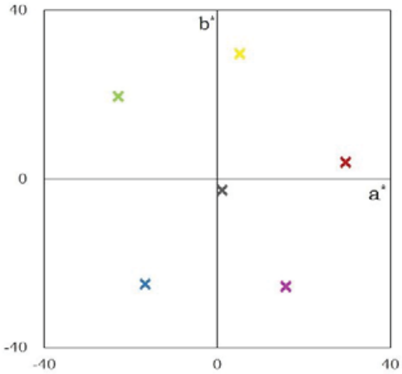

Figure 3. *The target colours plotted in CIELAB a^*b^* plane.*

Table 2. The CIELAB coordinates for the background colours to study the lightness contrast effect

		R	Y	G	B	M	Grey
	L^*_1	0	0	0	0	0	0
	L^*_2	/	/	/	/	/	10
	L^*_3	20	20	20	20	20	20
	L^*_4	/	/	/	/	/	30
h^*_{ab}=293.9 C^*_{ab}=3	L^*_5	40	40	40	40	40	40
	L^*_6	50	50	50	50	50	50
	L^*_7	60	60	60	60	60	60
	L^*_8	/	/	/	/	/	70
	L^*_9	80	80	80	80	80	80
	L^*_{10}	/	/	/	/	/	90
	L^*_{11}	/	/	/	/	/	100

Table 3. The CIELAB coordinates for the background colours to study hue contrast effect

		R	Y	G	B	M
	h^*_1	247.4	319.9	19.5	116.4	181.9
	h^*_2	287.4	359.9	59.5	156.4	221.9
	h^*_3	307.4	19.9	79.5	176.4	241.9
	h^*_4	322.4	34.9	94.5	191.4	256.9
	h^*_5	337.4	49.9	109.5	206.4	271.9
	h^*_6	352.4	64.9	124.5	221.4	286.9
L^*=50 C^*_{ab}=30	h^*_7	22.4	94.9	154.5	251.4	316.9
	h^*_8	37.4	109.9	169.5	266.4	331.9
	h^*_9	52.4	124.9	184.5	281.4	346.9
	h^*_{10}	67.4	139.9	199.5	296.4	1.9
	h^*_{11}	87.4	159.9	219.5	316.4	21.9
	h^*_{12}	127.4	199.9	259.5	356.4	61.9
	h_{13}	187.4	259.9	319.5	56.4	121.9
L^*=50 C^*_{ab}=3	h^*_{14} (grey)	293.9	293.9	293.9	293.9	293.9

For investigating the hue contrast effect, five series of colours (Red, Yellow, Green, Blue, Magenta) were prepared for matching.

Test 'X' of each target 'X' was against 13 backgrounds only differed in hue (h^* + 180, h^* ± 120, h^* ± 80, h^* ± 60, h^* ± 45, h^* ± 30, h^* ± 15, where h^* is the CIELAB hue angle of the target; they all had L^* of 50, C^*_{ab} of 30) together with one neutral grey. Taking 'Red' target as an example, Figure 4 plots the CIELAB coordinates of background colours for 'Red' colour centre. Table 3 shows CIELAB coordinates of the backgrounds in the five hue series. This results in a total of 70 combinations for each observer, i.e., 5 targets x 14 backgrounds.

Twenty normal colour vision observers participated in the experiment including ten males and ten females. In total, 2640 matches were accumulated, i.e., [5 target colours × (13 coloured backgrounds + 7 grey backgrounds) + 1 target colour × 11 backgrounds + 21 repeats] × 20 observers.

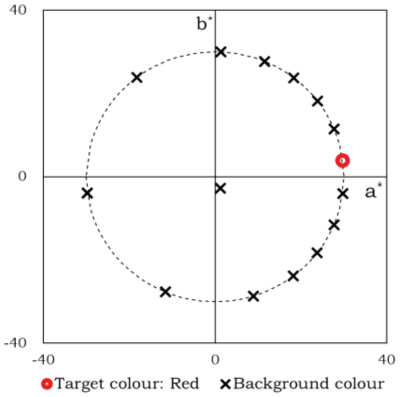

*Figure 4. The colour distribution of background colours for 'Red' target in CIELAB a*b* plane.*

Result & Discussion

Observer variation

Mean Colour Difference from the Mean (MCDM) were calculated to represent the observer variation of the result. Table 4 summarizes the MCDM values. All colour differences were calculated using CAM16-UCS colour space. The intra-observer variation describes the repeatability between the single observer's two repeats while the inter-observer variation describes the consistency between all observers. The overall MCDM was found to be 2.9 $\Delta E'_{Jab}$ (total colour difference) and 2.4 $\Delta E'_{ab}$ (chromatic colour difference, without lightness component) for inter-observer variations. The intra- observer variations are 1.3 $\Delta E'_{Jab}$ and 1.1 $\Delta E'_{ab}$. The degree of observer consistency is considered to be highly satisfactory.

Table 4. MCDM values for characterizing the inter- and intra-observer variations.

	Inter	Intra
$\Delta E'_{Jab}$	2.9	1.3
$\Delta E'_{ab}$	2.4	1.1

Modelling the lightness Simultaneous Contrast Effect in CAM16

To reveal the contrast effect, the visual results were expressed as each test/background combination. The reference background on the left was always set to the neutral colour of L^*=50, the differences in lightness $\Delta J'_v$ represents the visual lightness shifts between the results of test/background and the target/reference (target/L^* =50). The differences in lightness $\Delta J'_{b\text{-}t}$ was the lightness differences between test background and target colour (the results of target/L^* =50).

Figure 5 shows the plot of $\Delta J'_v$ against $\Delta J'_{b\text{-}t}$ for all the six series of target colours, the colour coding scheme of the dots corresponding to the target colour of the series, i.e., Red, Yellow, Green, Blue, Magenta and Neutral grey.

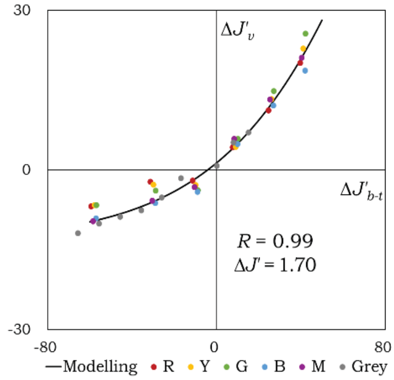

Figure 5. The plot between the visual lightness difference, $\Delta J'_v$ plotted against the $\Delta J'_{b\text{-}t}$ between the test background and target colour for all colour combinations.

Figure 5 shows a clear trend, i.e., a darker background will make centre brighter. The trend was later modelled by a sigmoidal function, as given in Equation (1).

$$\Delta J'_{cc} = \frac{16.0067}{0.0837 + e^{-0.0240 \times \Delta J'_{b-t}}} - 13.4455 \tag{1}$$

The model was fitted by minimizing the colour difference between visual colour shift ($\Delta J'_v$) and $\Delta J'_{cc}$ (Equation (1)) using a root mean square. The fitted sigmoidal function is also plotted in Figure 5. It can be seen that the model fitted well to all the data points, having a lightness difference of 1.70 and a correlation coefficient of 0.99.

Modelling the Hue Simultaneous Contrast Effect in CAM16

As mentioned earlier, taking target/grey background as a reference, the differences in hue angle $\Delta h'_v$, representing the visual colour shifts between the results of test/background and the target/reference (target/grey background), were calculated. The differences in hue angle $\Delta h'_{b\text{-}t}$ were the colour differences between coloured background and target colour (the result of target/grey background). All the parameters were calculated using CAM16-UCS.

The hue metric differences $\Delta H'_v$ and $\Delta H'_{b\text{-}t}$ were determined from the hue angle differences $\Delta h'_v$ and $\Delta h'_{b\text{-}t}$, using Equation (2) to make the same visual scale as the lightness and chroma differences for all test/background combinations. Figure 6 shows the $\Delta H'_v$ plotted against $\Delta H'_{b\text{-}t}$ for five series of target colours.

$$\Delta H = 2 \times (C_1 C_2)^{0.5} \sin(\frac{\Delta h}{2}) \tag{2}$$

where C_1 and C_2 are the CAM16-UCS chroma.

It can be seen that the results show a clear relation of sine function. Based on the data, hue simultaneous colour contrast was modelled as given in Equation (3).

$$\Delta H'_{cc} = 0.4408 \times \Delta H'_{b-t} \times e^{-0.001 \times (\Delta H'_{b-t})^2} \quad (3)$$

A sine function was well fitted to consider the hue of the background, also plotted in Figure 6. The equation modelled the hue contrast effect by showing a transition at the turning point of zero (representing the hue composition of the target). In its both sides, the sign of colour difference changes from negative to positive. It had an R of 0.95 and $\Delta H'$ of 1.52.

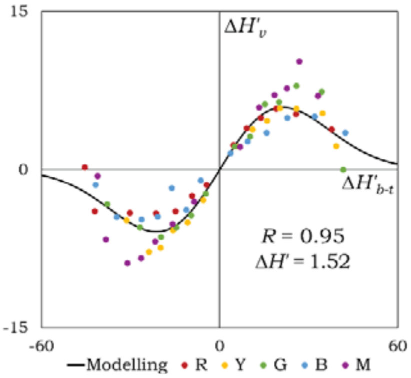

Figure 6. Hue difference, $\Delta H'_v$ of the visual colour shifts plotted against the $\Delta H'_{b-t}$ between test background and target colour (the result of target/grey background), for all colour combinations.

In this section, the lightness and hue contrast effects were successfully modelled by Equation (2) and Equation (3). Both were integrated into CAM16, called CAM16cc here. In the computation, the background and target colour information need to be inputted. The lightness effect ($\Delta J'_{cc}$) will be calculated before the calculation of hue effect ($\Delta H'_{cc}$). Figure 7 shows the flow chart of the modelling. Note that chroma contrast effect was not studied. From the Gao *et al.*'s results [6], they concluded that the chroma effect is much smaller than the lightness and hue contrast effect, and chroma effect is partly affected by both the lightness and hue. So, it is not studied here.

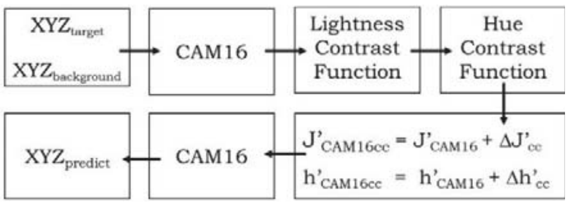

Figure 7. The flow chart of CAM16cc.

Verifying the model by previous datasets

The model was also verified using two independent datasets, i.e., one was generated by Wang *et al.* using the magnitude estimation method on patches (only hue contrast) and two was built by Wu *et al.* using the colour matching method with a small field of view (both hue and lightness contrast). The data were obtained from a series of large-scale psychophysical experiments. The experimental settings were under well controlled and the testing colours were selected carefully. The results show a clear trend with high reliability.

Table 5. The predictive performance of CAM16cc model in terms *of ΔJ' (or ΔH').*

	Dataset		Wang	Wu	Present
General Information	Num. of target		30	10	6
	Num. of background		3	19	20
	Num. of observer		10	9	20
	Num. of estimate		90	174	132
CAM16cc	Lightness	ΔJ'	/	5.03	1.70
	Hue	ΔH'	3.35	3.72	1.52
Refined CAM16cc	Hue	ΔH'	3.11	0.77	/
		Scaling factor	0.69	0.15	/

Table 5 shows the predictive performance. In general, the model predicts well to the trend but the extend of the effect is depending on the experimental conditions, e.g., a much larger effect was found from those set to a large field of view (FOV). This implies that the contrast effect is dependent upon the experimental conditions to a great extent, especially the hue contrast. Thus, the former hue contrast model was modified by multiplying a constant.

(a)

(b)

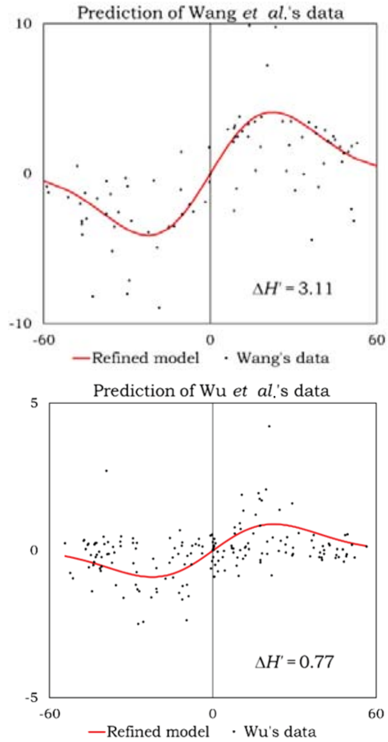

Figure 8. The prediction performance of refined CAM16cc to fit (a) the Wang et al. 's data and (b) the Wu et al. 's data.

Table 5 and Figure 8 also shows the predictive performance after modification which improved significantly. The size of FOV in the Wang *et al.* 's experiment was similar with the present study, while that in the Wu *et al.* 's experiment was much smaller. Thus, the coefficient of Wang *et al.* is closer to one, and that of Wu *et al.* was closer to zero. The relationship between the magnitude of the contrast effect and FOV of the background require further study.

Conclusion

Visual experiments were carried out to investigate the simultaneous colour contrast effect on a self-luminous display using colour matching method. The goal is to accumulate a new visual dataset and the data can be used to extend CAM16 to accurately predict the simultaneous colour contrast effect. Five coloured targets together with a neutral grey were studied. A total of 132 test/background combinations were presented. Twenty normal colour vision observers participated in the experiment. In total, 2,640 matches were accumulated.

The results clearly showed that the lightness of the test colour decreased with the lightness of the background colour. And the direction of the hue contrast was in the opposite direction to the background colours and followed the opponent-colour theory. Also, the hue contrast was enhanced when the background colour is close to the target colour.

The results were used to extend CAM16 to predict colour contrast effect, including a sigmoidal function for lightness contrast effect and a sine function for hue colour contrast. The model was well fitted to the visual data, since the errors of prediction were $\Delta J'$ and $\Delta H'$ were 1.70 and 1.52 respectively. Two large-scale independent datasets were also used to test this new model, including Wang *et al.*'s and Wu *et al.*'s data. The model predicts well to the data but a systematic discrepancy was found for each dataset due to different viewing conditions. By simply multiplying a constant to the function for each dataset, the accuracy of prediction improved greatly. This implies that there is a clear trend of contrast effect, but the viewing condition has an impact on the magnitude of the effect.

Acknowledgement

The authors like to thank the support from the Chinese Government's National Science Foundation (Project Number on 61775190).

References

[1] R. W. G. Hunt, "A model of colour vision for predicting colour appearance", J. Color Research & Application, 7(2), 95-112 (1982).

[2] M. R. Luo, Encyclopaedia of Colour Science and Technology, (Springer, Berlin, 2015)

[3] D. Jameson, L. M. Hurvich, "Theory of brightness and color contrast in human vision", J. Vision Research, 4(1-2), 135-154 (1964).

[4] M. R. Luo, X. W. Gao, "Quantifying colour appearance. part V. simultaneous contrast", J. Color Research & Application, 20(1), 18-28 (1995).

[5] R. C. Wu, R H. Wardman, "Proposed modification to the CIECAM02 colour appearance model to include the simultaneous contrast effects", Color Research & Application, 32(2), 121-129 (2010).

[6] X. W. Gao, Y. Wang, Y. Qian, A. Gao, "Modelling of chromatic contrast for retrieval of wallpaper images", J. Color Research & Application, 40(4), 361-373 (2015).

[7] R. W. G. Hunt, "Revised colour-appearance model for related and unrelated colours", J. Color Research & Application, 16(3), 146 - 165 (1991).

[8] R. W. G. Hunt, "An improved predictor of colourfulness in a model of colour vision", J. Color Research & Application, 19(1), 23-26 (1994).

[9] R. W. G. Hunt, M. R. Luo, "Evaluation of a model of colour vision by magnitude scalings: discussion of collected results", J. Color Research & Application, 19(1), 27-33 (1994).

[10] M. R. Luo and R. W. G. Hunt, "The structures of the CIE 1997 colour appearance model (CIECAM97s)", J. Color Research & Application, 23(3), 138-146 (1998).

[11] CIE 159:2004, A colour appearance model for colour managmeng systems: CIECAM02, (CIE, Vienna, 2004).

[12] C. J. Li. Z. Li, Z. Wang, Y. Xu, M. R. Luo, G. H. Cui, M. Melgosa, M. H. Brill, M. R. Pointer, "Comprehensive color solutions, CAM16, CAT16 and CAM16-UCS", J. Color Research & Application, 42(6), 703-718 (2017).

[13] M. R. Luo, A.A. Clarke, P. A. Rhodes, A. Schappo, S. A. R. Scrivener, C. J. Tait, "Quantifying colour appearance: Part I – LUTCHI colour appearance data", J. Color Research & Application, 16(3), 166-180 (1991).

[14] M. R. Luo, A. A. Clarke, P. A. Rhodes, A. Schappo, S. A. R. Scrivener, C. J. Tait, "Quantifying colour appearance: Part II – Testing colour models' performance using LUTCHI colour appearance data", J. Color Research & Application, 16(3), 181-197 (1991).

[15] M. R. Luo, X. W. Gao, P. A. Rhodes, H. J. Xin, A. A. Clarke, S. A. R. Scrivener, "Quantifying colour appearance: Part III - Supplementary LUTCHI colour appearance data", J. Color Research & Application, 18(2), 98-113 (1993).

Author Biography

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