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Accumulation of Corresponding Colours Under Extreme Chromatic Illuminations and modification of CAM16

Yuechen Zhu[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

The goal of this study was to investigate the chromatic adaptation under extreme chromatic lighting conditions using the magnitude estimation method. The locations of the lightings on CIE1976 $u'v'$ plane were close to the spectrum locus, so the colour purity was far beyond the previous studies, and the data could test the limitations of the existing models. Two psychophysical experiments were carried out, and 1,470 estimations of corresponding colours were accumulated. The results showed that CAT16 gave a good prediction performance for all the chromatic lightings except for blue lighting, and the degree of adaptation was relatively high, that is, D was close to 1. The prediction for blue lightings was modified, the results showed the performance of CAM16 could be improved by correcting the matrix instead of the D values.

Introduction

The human visual system is able to approximately determine the colours of objects irrespective of the illuminant. Chromatic adaptation is a visual phenomenon to consider the change of colour appearance due to different illuminants, producing a colour constancy. Chromatic adaptation transforms (CATs) were developed to predict the corresponding colours. CIE TC1-52 has been investigated the chromatic adaptation transforms and produced a technical report [1] to summarise the state-of-the-art CATs. Amongst different CATs, the CAT02 [2], CMCCAT2000 [3], Sharpe sensors [4] gave similar performance and they performed better than the others. CAT02 embedded in CIECAM02 since has been widely used.

In the past several years, the findings of several psychophysical studies suggested that the existing CATs did not perform well under illuminants having low CCT and low luminance [5]. Zhai *et. al.* carried out an experiment using both surface colour stimuli and self-luminous colour stimuli to collect corresponding white colours under the adapting conditions with various CCT and D_{uv} levels and found a lower degree of chromatic adaptation when viewing self-luminous colour stimuli [6]. Zhu *et. al.* carried out two experiments using memory matching method on a self-luminous to investigate whether the adapting luminance and chromaticities jointly affect the degree of chromatic adaptation [7]. Both of adapting luminance and chromaticities were found to significantly affect the degree of chromatic adaptation, with a lower degree under the adapting condition at a lower CCT, which revealed the weakness of CAT02. And a new CIE technical committee knowed as JTC10 was formed to recommend the CAT16 and CAM16 [8] because there are some mathematic problems in CIECAM02.

The most widely used visual data on chromatic adaptation are corresponding colours (CC) [9]. Corresponding colours are defined as two stimuli, viewed under differing viewing conditions, that match in colour appearance. However, for most existing corresponding colours datasets, the adapting conditions were restricted to neutral illuminants differed in CCT and luminance level. Thus, extreme chromatic lighting conditions were not considered and there are few researches on that. McCann *et. al.* [10] conducted four phases of experiments to obtain corresponding colours using a white illuminant and four chromatic illuminants using a successive haploscopic matching technique. A Mondrian figure consisting of 18 object colours was used. The illuminants used ranged from 14 lux to 40 lux, i.e., very dark lighting conditions. The original data were not published using standard colorimetric notations. Nayatani *et. al.* derived a method to transform the original data into standard colorimetric form. Smet *et. al.* [11-12] used a projector to change the chromaticities of the adapting field and to collect corresponding colors for five familiar objects against nine coloured illuminants. It was found that the present CATs failed to account for the degree of adaptation when the colour of the illumination becomes more chromatic. But the colour purity of the illuminants used in these studies are not high enough.

The goal of this study is to investigate the chromatic adaptation under extreme chromatic lighting conditions. Two psychophysical experiments were conducted including low and high luminance. The locations of the lightings on CIE1976 $u'v'$ plane were close to the spectrum locus, so the colour purity was far beyond the previous studies, and the data could test the limitations of the existing models.

Methods

Apparatus

The experiment was conducted in a Thouslite LEDView cabinet with a mid-grey interior (L^*=70). It includes 14 LED channels including 11 in the visible spectrum range and 3 in the UV range. It can accurately reproduce a measured or imported spectrum and keep same illuminant properties during illuminant switch without warm up time.

A JETI Specbos 1411 spectroradiometer was used to calibrate the illumination conditions in the viewing booth and to measure the spectra of the samples at 45 deg. CIE 1964 standard colorimetric observer was used to calculate the XYZ values.

Experimental technique

Magnitude estimation [13] method was used in this study. Although its precision is lower than that of matching method, the normal viewing conditions and steady state of adaptation which are important to chromatic adaptation could be achieved. For each estimation, colourfulness and hue were assessed. For scaling colourfulness, a reference colour (an orange sample) placed under D65 was used as a reference to be memorised (assigned a colourfulness of 50). For All the colours under the chromatic lightings were scaled against that reference colour, the results were marked as M_v'. For scaling hue, the concept of unitary hues was used, i.e., pure red, yellow, green, blue and back to red. Each colour was scaled according to one or mixture of two unitary hues, and the result was expressed as hue composition ranged from 0 to 400, red corresponds to 0 (or 400), yellow corresponds to 100, green corresponds to 200, blue corresponds to 300. For example, an orange sample may be described as '70R30Y', which means there is 70% red and 30% yellow in this colour, so the hue composition (H_v') was 70.

Procedure

The experiments were conducted in a darkened room. Instructions for the estimation task were verbally provided for each observer. At the beginning of the experiment, a reference sample of reference colourfulness (assigned a colourfulness of 50) was presented under D65 and observers were asked to memorize it. For each lighting condition, observers were given a set of samples in random order. They were asked to sort the samples by colour circle first (see Figure 1). Then, they picked out and reported the colourfulness and hue of each sample individually in random order. Until all the estimations were accumulated, the light was switched to the next one. And observer should repeat the 'adapt-sort-estimate' process. The adapting time was set to 10 minutes to get a stable adaptation. The viewing angle was fixed at 45 degrees.

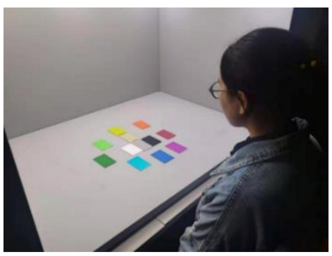

Figure 1. *The experimental situation.*

Experiments

Experiment 1: Illuminants with low luminance

Adapting conditions and samples

Five adapting conditions were designed including four chromatic illuminants (Red, Yellow, Green, Blue) and one neutral light (D65, R_a=94). Single channel of the cabinet was used to obtain extreme chromatic illuminants, and a minute amount of white light was added to increase the luminance level. Figure 2 shows the relative spectral power distributions of the adapting conditions. Figure 3 illustrates the appearance of each adapting condition. As mentioned, the locations of the lightings on CIE1976 $u'v'$ plane were close to the spectrum locus (see Figure 4). The luminance of each lighting was approximately set to 40 cd/m^2. Table 1 shows the colour coordinates of each illuminant.

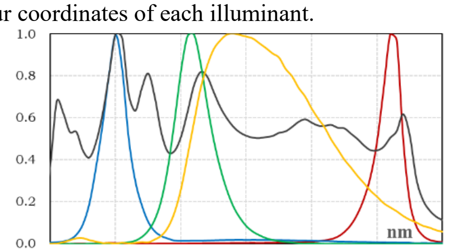

Figure 2. *The relative spectral power distributions of the adapting conditions (EXP1).*

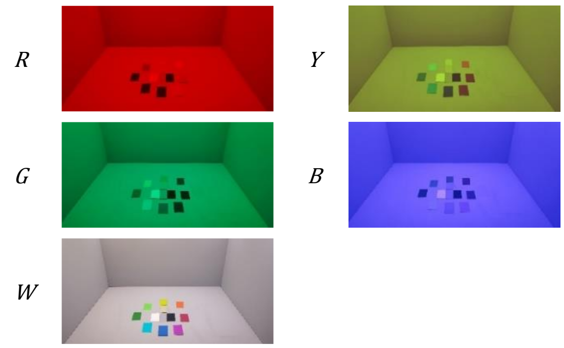

Figure 3. *Illustration of the adapting conditions (EXP1).*

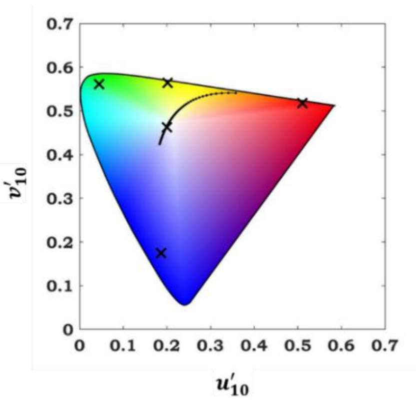

Figure 4. *The locations of adapting conditions on CIE1976 $u'v'$ plane (EXP1).*

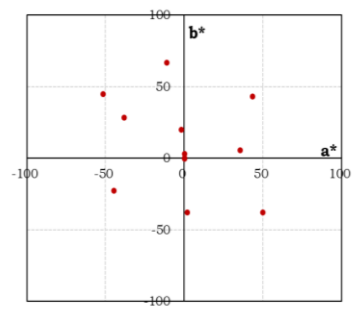

Figure 5. *The colour coordinates of samples on CIELAB a^*b^* plane (EXP1).*

Table 1. The colour coordinates of each illuminant (EXP1).

	X	Y	Z	u'	v'
R	95.2	40.5	2	0.5373	0.5143
G	6.2	41.3	16.4	0.0367	0.5507
B	143.5	41.8	672.6	0.2059	0.1349
Y	30	40.6	2.3	0.1858	0.5657
D65	40.8	41.7	48.9	0.2007	0.4616

To considering the colour distribution of the sample in colour space, nine coloured samples and three neutral samples were selected. The FOV (field of viewing) of the sample was 10 degrees.

Figure 5 shows the coordinates of 12 test samples in CIELAB a^*b^* plane, D65 was used as a reference white in the calculation. This results in a total of 75 estimations for each observer, i.e., 5 illuminants x (12 samples + 3 repeats).

Observers

Ten normal colour vision observers between 20 and 27 years of age (mean = 24.0, std = 1.8) participated in the experiment including five males and five females. In total, 750 estimations were accumulated, i.e., 5 illuminants × (12 samples + 3 repeats) × 10 observers.

Data processing

A large number of subjective data were obtained by magnitude estimation method. Thus, a scale conversion was performed before the numerical analysis. CAM16-UCS colour space proposed by CIE was used during the calculation. The raw visual data (H'_v, M'_v) should be transformed to normalized data in forms of J'_v, a'_v, b'_v.

Firstly, the predicted colour attributes (J'_c, M'_c, h'_c) of each sample under different illuminants were calculated by the reflectance of the sample, spectrum power distribution of the illuminants and colour matching function (CIE1964 Standard Colorimetric Observers). Figure 6 illustrates the computational process, the degree of adaptation (D) was set to 1. Because this study only focused on the chromaticities instead of the luminance, so the J'_v was equal to J'_c.

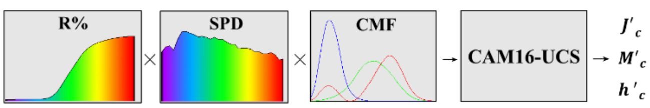

Figure 6. The computational process of the prediction of CAM16-UCS colour space.

And H'_v was transformed to h'_v using the Equation (1) and the data in Table 2. Choose a proper i (i = 1, 2, 3, or 4), so that $H_i \leq H'_v < H_{i+1}$.

$$h'_v = \frac{(H'_v - H_i)\cdot(e_{i+1}h_i - e_i h_{i+1}) - 100\cdot h_i \cdot e_{i+1}}{(H'_v - H_i)\cdot(e_{i+1} - e_i) - 100\cdot e_{i+1}} \quad (1)$$

Set $h'_v = h'_v - 360$, if $h'_v > 360$.

Table 2 Unique hue data for calculation.

	Red	Yellow	Green	Blue	Red
i	1	2	3	4	5
h_i	20.14	90.00	164.25	237.53	380.14
e_i	0.8	0.7	1.0	1.2	0.8
H_i	0.0	100.0	200.0	300.0	400.0

As for scale conversion of colourfulness, although each observer estimated the sample according to reference colourfulness, the numerical range was different among them. For example, the results given by some observers were ranged from 0 to 90, while others ranged from 0 to 150. Thus, the scale conversion was important, Equation (2) shows the data processing. Then, a'_v and b'_v can be easily obtained by M'_{v_scaled} and h'_v.

$$M'_{v\_scaled} = M'_v \times \left(\frac{\sum_{i=1}^{15} M'_{ci}}{\sum_{i=1}^{15} M'_{vi}}\right) \quad (2)$$

In conclusion, J'_v, M'_v, h'_v were transformed to J'_v, a'_v, b'_v, and the data can be used to test the existing CATs.

Results

Observer variation

Mean Colour Difference from the Mean (MCDM) were calculated to represent the observer variation of the result. Table 3 summarizes the MCDM values. All colour differences were calculated using CAM16-UCS colour space. The inter-observer variation describes the consistency between all observers. The MCDM values were ranged from 4.3 to 10.2 $\Delta E'_{ab}$ (chromatic colour difference, without lightness component), and mean value was 7.5. It can be found that the results of Yellow and D65 gave a high consistency, and the overall results were comparable to similar studies.

Table 3. MCDM values for characterizing the observer variations (EXP1).

	R	Y	G	B	D65	Mean
$\Delta E'_{ab}$	7.2	5.5	10.1	10.2	4.3	7.5

Testing the performance of CAM16 model

Using the reverse model of CAM16 and normalized data after data processing, the prediction performance of CAM16 and CAT16 was tested. Note that, the D (degree of chromatic adaptation) was set to 1 firstly. The outputs of the model were predicted XYZ values of the samples. And if the model could perform well under such extreme chromatic lighting conditions, the predicted XYZ values should be close to actual measured values. Figure 7 shows the results of testing. The distance of predicted values and measured values of each samples represented the accuracy of the prediction. It can be found that CAM16 and CAT16 gave a good prediction performance for all the chromatic lightings except for blue lighting. There was a significate error under blue lighting, that is the predicted results were far away from the measured results by the vector from lightings to the measured results.

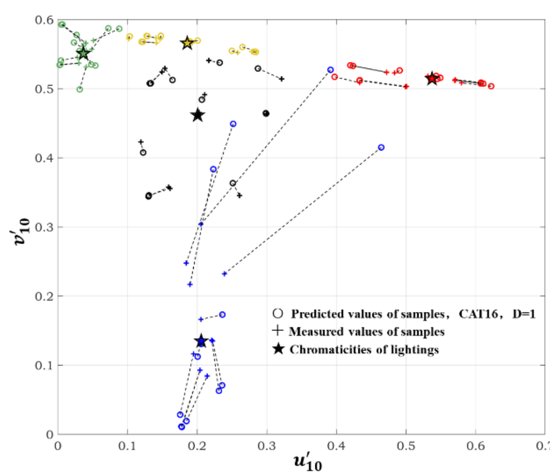

Figure 7. The prediction performance of CAM16 model in Experiment 1 (D=1).

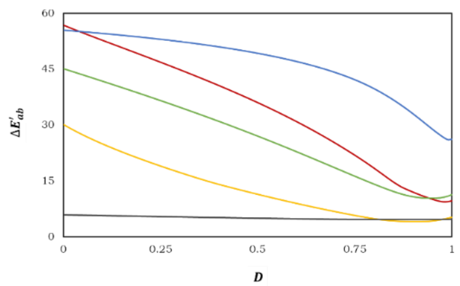

Figure 8. *Optimization results of each adapting condition in Experiment 1 (0⩽ D⩽1).*

Then, optimization on the degree of chromatic adaptation (D factor) for each adapting condition to minimize the prediction errors (characterized using $\Delta E'_{ab}$) was performed. Figure 8 shows the optimization results. The results showed the degree of adaptation was relatively high, that is, D was close to 1.

Experiment 2: Illuminants with high luminance

Adapting conditions and samples

Three adapting conditions were designed including two chromatic illuminants (Red, Blue) and one neutral light (4500K). Figure 9 shows the relative spectral power distributions of the adapting conditions. As mentioned, the locations of the lightings on CIE1976 $u'v'$ plane were close to the spectrum locus (see Figure 10). The neutral light was obtained through a blue LED chip coated with a yellow phosphor, which is common to current LED household light. Table 4 shows the colour coordinates of each illuminant.

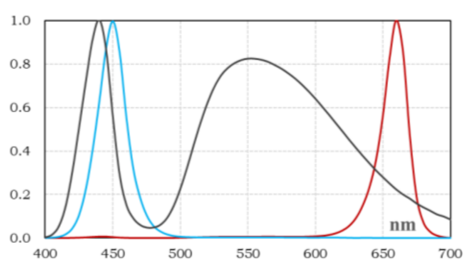

Figure 9. *The relative spectral power distributions of the adapting conditions (EXP2).*

Table 4. The colour coordinates of each illuminant (EXP2).

	X	Y	Z	u'	v'
R	384.1	178.91	19.61	0.4914	0.5150
B	503.8	159.9	2675.3	0.1844	0.1317
D65	1834.3	1879.0	1328.7	0.2158	0.4973

Thirteen samples were selected including 12 samples used in Experiment 1. A red sample was added for the lack of red in the former experiment. Figure 11 shows the coordinates of 13 test samples in CIELAB a^*b^* plane, D65 was used as a reference white in the calculation. This results in a total of 48 estimations for each observer, i.e., 3 illuminants x (13 samples + 3 repeats).

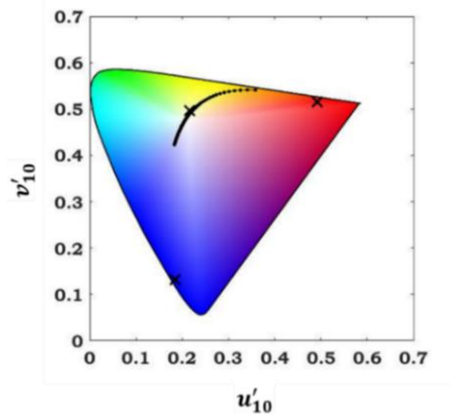

Figure 10. *The locations of adapting conditions on CIE1976 $u'v'$ plane (EXP2).*

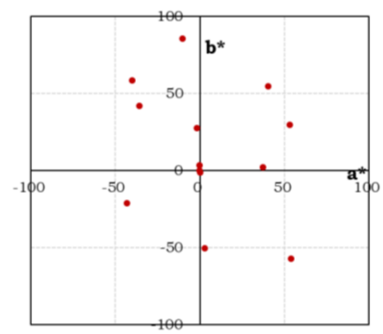

Figure 11. *The colour coordinates of samples on CIELAB a^*b^* plane (EXP2).*

Observers

Fifteen normal colour vision observers between 19 and 27 years of age (mean = 24.0, std = 2.0) participated in the experiment including eight males and seven females. In total, 720 estimations were accumulated, i.e., 3 illuminants × (13 samples + 3 repeats) × 15 observers.

Results

Same as Experiment 1, the visual raw data (H'_v, M'_v) were transformed to normalized data in forms of J'_v, a'_v, b'_v.

Observer variation

Inter-observer variations in terms of MCDM were ranged from 6.5 to 13.5 $\Delta E'_{ab}$ (chromatic colour difference, without lightness component), and mean value was 9.0. Table 5 summarizes the MCDM values. The overall results were similar to the former experiment.

Table 5. MCDM values for characterizing the observer variations (EXP2).

	R	B	D65	Mean
$\Delta E'_{ab}$	6.9	13.5	6.5	9.0

Testing the performance of CAM16 model

Firstly, the prediction performance of CAM16 and CAT16 was also tested, and the D was set to 1. Figure 12 shows the testing results. It can be found that the results were similar to the

Experiment 1, which CAM16 and CAT16 gave a good prediction performance for all the chromatic lightings except for blue lighting.

Then, optimization on the degree of chromatic adaptation factor D was performed. Figure 13 shows the optimization results. The results also showed the degree of adaptation was relatively high, that is, D was close to 1.

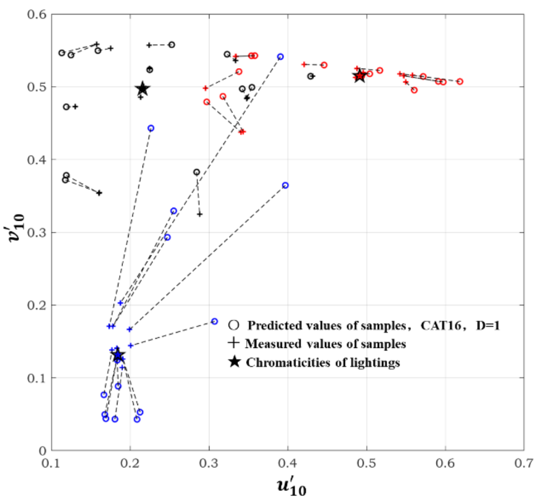

Figure 12. The prediction performance of CAM16 model in Experiment 2 (D=1).

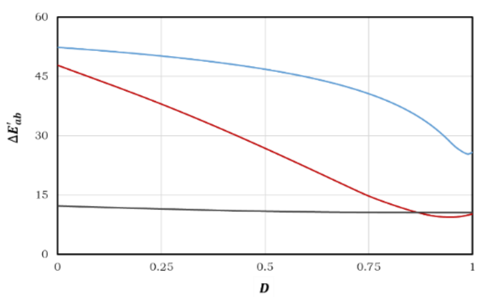

Figure 13. Optimization results of each adapting condition in Experiment 2 (0 ≤D≤1).

Comparing the results of experiment 1 with experiment 2, it can be found that the results show highly consistency and the performance of CAM16 and CAT16 remain stable. The luminance level had very little influence on that.

Modification of CAM16 in blue region

It is suggested that CAM16 should be modified to predicted the chromatic adaptation for blue lightings. Firstly, the colour adaptation of the illuminant in the corresponding cone response space was investigated. The optimized D for each cone response was performed (D_r, D_g, D_b) to minimize the prediction errors. Table 6 shows the results of optimization.

Table 6. The performance of optimized *D* for each cone response.

	D_r	D_g	D_b	Prediction error ($\Delta E'_{ab}$)
EXP1	0.87	0.96	0.07	25.86
EXP2	0.86	0.77	0.06	25.38

It can be found that the prediction errors of Experiment 1 reduced from 26.05 to 25.86 $\Delta E'_{ab}$, and the prediction errors of Experiment 2 reduced from and 25.86 to 25.38 $\Delta E'_{ab}$. The results indicated that the performance of CAM16 could not be improved by correcting the D values.

Thus, the matrix coefficients of CAT should be revised. Equation (3) illustrates the third-order matrix of CAT. In order to improve the performance of CAM16 in blue region, three coefficients in the third row (i.e., a_7, a_8, a_9) should be corrected. Table 7 shows the results of optimization.

$$M = \begin{bmatrix} a_1 & a_2 & a_3 \\ a_4 & a_5 & a_6 \\ a_7 & a_8 & a_9 \end{bmatrix} \quad (3)$$

Table 7. The performance of optimized matrix coefficients.

	a_7	a_8	a_9	Prediction error ($\Delta E'_{ab}$)
EXP1	-0.10	0.01	1.09	12.45
EXP2	-0.10	0.00	1.10	14.17

It can be found that the prediction errors of Experiment 1 reduced from 26.05 to 12.45 $\Delta E'_{ab}$, and the prediction errors of Experiment 2 reduced from and 25.86 to 14.17 $\Delta E'_{ab}$. The results suggested that the performance of CAM16 could be greatly enhanced by correcting the matrix. However, there is too little data to be able to derive a generalizable model. More studies that investigate the chromatic adaptation in blue lightings are needed to draw a quantitative conclusion.

Conclusion

Visual experiments were carried out to investigate the chromatic adaptation under extreme chromatic lighting conditions using magnitude estimation method. The locations of the lightings on CIE1976 $u'v'$ plane were close to the spectrum locus, so the colour purity was far beyond the previous studies, and the data could test the limitations of the existing models. Two psychophysical experiments including low and high luminance were carried out, and 1,470 estimations of corresponding colours were accumulated. A reasonable scale conversion was performed before the numerical analysis. And the data were used to test the performance of CAM16 and CAT16.

The results showed that CAM16 and CAT16 gave a good prediction performance for all the chromatic lightings except for blue lighting, and the degree of adaptation was relatively high, that is, D was close to 1. And the luminance level had very little influence on that.

The prediction for blue lightings was modified, the results showed the performance of CAM16 could be improved by correcting the matrix instead of the D values.

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Author Biography

Yuechen Zhu received her doctorate from School of Optical Science and Engineering, Zhejiang University, Hangzhou, China. Now she is a post-doctor at Zhejiang University. Her research interests include colour science and image engineering.