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Change of color appearance due to extremely high light level: corresponding colors under 100 and 3000 cd/m^2

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Abstract

Great efforts have been made to develop color appearance models to predict color appearance of stimuli under various viewing conditions. CIECAM02, the most widely used color appearance model, and many other color appearance models were all developed based on corresponding color datasets, including LUTCHI data. Though the effect of adapting light level on color appearance, which is known as "Hunt Effect", is well known, most of the corresponding color datasets were collected within a limited range of light levels (i.e., below 700 cd/m^2), which was much lower than that under daylight. A recent study investigating color preference of an artwork under various light levels from 20 to 15000 lx suggested that the existing color appearance models may not accurately characterize the color appearance of stimuli under extremely high light levels, based on the assumption that the same preference judgements were due to the same color appearance. This article reports a psychophysical study, which was designed to directly collect corresponding colors under two light levels—100 and 3000 cd/m^2 (i.e., ≈ 314 and 9420 lx). Human observers completed haploscopic color matching for four color stimuli (i.e., red, green, blue, and yellow) under the two light levels at 2700 or 6500 K. Though the Hunt Effect was supported by the results, CIECAM02 was found to have large errors under the extremely high light levels, especially when the CCT was low.

Introduction

Color is a perceptual response which is triggered by emitted or reflected optical radiation and processed by human visual system [1]. The spectral power distribution (SPD) of an illuminant and the spectral reflectance of an object jointly determine the object color [2]. However, there are other factors that affect the color appearance of an object, such as adapting conditions. Light level was found to significantly affect color appearance in Hunt's study in 1952 [3]. It was addressed in 'Hunt effect' that the colorfulness of a color sample is increased as the light level gets higher.

Human visual system is typically assumed to process color at two levels, with one dealing with trichromatic visual response and the other dealing with chromatic visual response [4].Based on this assumption, great efforts have been made to develop color appearance models to predict color appearance under different lighting conditions [5-7]. Color appearance models are aimed to mathematically predict and model perceptual color appearance under various adapting conditions. The widely used color appearance model—CIECAM02 quantifies color appearance on the basis of LUTCHI color appearance data. In the visual experiments aimed to collect this set of color data, observers were asked to make magnitude estimation on color samples under different adapting conditions. The series of experiments were carried out under different light sources, luminance levels, background conditions, and on different viewing media. Therefore, CIECAM02 is capable of predicting color appearance under a wide range of viewing conditions and across different media. The luminance levels used in the experiments were mainly lower than 700 cd/m^2 and only four color samples were quantified between 1000 and 1280 cd/m^2 [5, 6]. However, people may experience a wide range of luminance levels (from 10^{-6} to 10^{+6} cd/m^2) in their daily life and the change of light levels involved in color reproduction between different lighting applications can be extremely large [8]. Although Hunt effect is considered in CIECAM02, several recent studies [9-11] have reported that the model did not perform well in predicting color appearance under the light levels outside the typical range for general illumination. It was revealed in our recent study [9] that CIECAM02 may overestimate the effect of light level on color appearance. Kim et al. [11] developed a revised color appearance model (herein after referred to as CAMHE) which aims to model color perception under extended light levels.

In this study, a visual experiment was carried out to collect corresponding color data under low photopic and very high light levels (i.e., from 100 to 3000 cd/m^2) using simultaneous haploscopic color matching technique. The experiment was designed to vary the luminance levels in the matching field to match the same stimulus in the reference field. The luminance at the reference field was set at 100 cd/m^2 while the luminance levels at the matching field were 100 and 3000 cd/m^2. The effect of light levels on color appearance was evaluated based on the visual results. The collected data were also used to verify the performance of CIECAM02 under different light levels.

Method

Apparatus

The visual experiment was conducted using two side-by-side viewing booths, with the inner walls being painted with Munsell N7 spectrally neutral paint. The dimensions of the booths were 60 cm (width) × 60 cm (depth) × 60 cm (height). Two spectrally tunable LED devices were used to provide uniform illumination to the two booths, with one being placed above each booth. Two 4.5 cm × 4.5 cm openings were cut on the back walls, with one in each booth, which was used to present color stimuli. The front openings of the two booths were partially covered by a black cloth, so that the observers could not see the LED devices. A chin rest was mounted just outside the viewing booths, aligning the sagittal plane of an observer with the walls between the two booths. Figure 1 shows the setup of the experiment.

Two spectrally tunable LED devices were placed behind the two viewing booths, with one behind each booth, to let the light penetrate through the openings on the back walls. A diffuser was attached to the back of the opening, so that the stimuli had a Lambertian distribution. In this study, the stimuli presented in the left booth, which was produced by the 11-channel spectrally tunable LED device, were always employed as the reference stimuli. The observers adjusted the color appearance of the stimuli in the right booth, which was produced by a four-channel spectrally tunable LED device, to match the appearance of the stimuli in the left booth.

The four-channel spectrally tunable LED device was connected to a DMX controller, which was connected to a desktop. A customized MATLAB program was developed, so that the observers can use six keys in the numerical section on a keyboard to change the color appearance of the stimuli in the Hue-Saturation-Intensity (HSI) color space. Specifically, the four error keys changed the hue and saturation; the "+" and "-" keys changed the intensities.

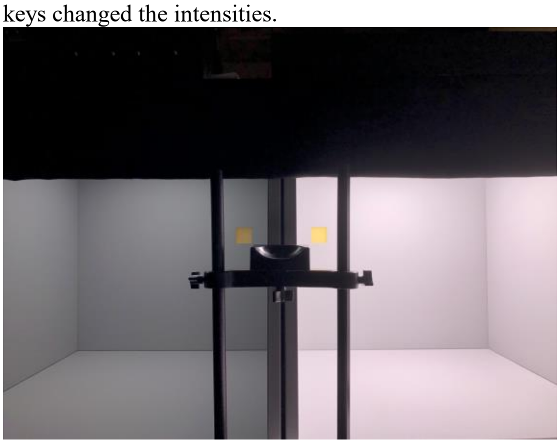

Figure 1. *Photograph for the experimental setup.*

Adapting conditions and stimuli

Two adapting conditions with chromaticities on Planckian locus were set for the reference field, comprising two CCT levels of 2700 and 6500 K and one luminance level (i.e., L_w) of 100 cd/m^2. Four adapting conditions with chromaticities on Planckian locus were set for the matching field, comprising two CCT levels (i.e., 2700 and 6500 K) and two luminance levels (i.e., $L_w \approx 100$ and 3000 cd/m^2). Four self-luminous colors (i.e., red, green, blue, and yellow) generated by the LEDCube were used as matching targets. The luminance of the self-luminous colors were between 57.5 and 65.6 cd/m^2. The reference stimuli always appeared at the left viewing window and the matched colors appeared at the right window.

All the adapting conditions were calibrated using a calibrated JETI Specbos 1411UV spectroradiometer and a calibrated Labsphere reflectance standard being placed at the center of the viewing booth. The colorimetric characteristics of the adapting conditions were calculated using CIE 1964 10° Color Matching Functions (CMFs) and the measured SPDs, as summarized in Table 1.

Table 1. Colorimetric characteristics of the adapting conditions.

	Left		Right			
Nominal L_w (cd/m^2)	100	100	100	3000	100	3000
Nominal CCT (K)	2700	6500	2700	2700	6500	6500
L_w (cd/m^2)	97	110	90	3193	118	3317
CCT (K)	2790	6547	2731	2658	6526	6532
D_{uv}	+0.0025	+0.0021	+0.0024	-0.0004	+0.0028	-0.0071
CRI-R_a	97.4	90.5	87.4	91.5	91.2	83.2
IES-R_f	95.7	88.9	86.9	88.8	85.0	85.5

Observers

Seven observers (6 males and 1 female) between 22 and 32 years of age (mean = 26.3, std. dev. = 3.35) participated in the experiment. All the observers were Asians and had normal color visions, as tested using 24 Plate Ishihara Color Vision Test. Each observer made twenty pairs of haploscopic color matching at the right viewing window (i.e., two CCT levels × two adapting luminance levels of the matching field × four colors of the reference stimuli + repeated four pairs of a random stimulus for assessing intra-observer variations).

Experimental Procedures

Upon arrival, the observers firstly completed a personal information survey and the Ishihara Color Vision test. Then the observers were escorted to the experimental area and given an explanation of the whole experiment. He or she was seated in front of the viewing booths with his or her chin being fixed on the chin rest. The general illumination in the space was then switched off. The observers were first required to look into the two viewing booths for two minutes for adaptation. The experiment employed simultaneous haploscopic viewing technique which means that the observers needed to adapt their left eyes to the reference illuminants in the left viewing booth and adapt their right eyes to the test illuminants in the right viewing booth at the same time. The LED devices behind the two viewing windows were switched off when the observers conducted the chromatic adaptation. After the adaptation, the observers were instructed to adjust the color shown at the right window in terms of hue and brightness to match the reference color at the left window using a Bluetooth keyboard. The observers could press the 'left' and 'right' key on the keyboard to change the hue, the 'up' or 'down' key to increase or reduce saturation, and press the '+' or '-' key to increase or reduce brightness. Starting chromaticity of the color at the right window was set to be distributed just around the chromaticity of the corresponding reference color to reduce the starting bias. Under each condition, each observer matched a random color twice for assessing the intra-observer variations. The entire experiment took about 1 hour.

When an observer completed the color matching under one condition, the experimenter recorded the chromaticities of the matched color and moved on the next condition. All the final answers under the corresponding adapting conditions were measured using a calibrated JETI Specbos 1411UV spectroradiometer and the colorimetric quantities were calculated with CIE 1964 10° CMFs.

Results and discussions

Intra- and inter- observer variations

The intra- and inter- observer variations were estimated by calculating the color difference in terms of $\Delta u'_{10}v'_{10}$. Each observer matched a random stimulus twice under each condition. The intra-observer variations were characterized by calculating the $\Delta u'_{10}v'_{10}$ for each observer for the repeated color sample under the same adapting condition. The median of the intra-observer color difference with the mean was 0.0066 *u'v'* units, which was smaller than the 0.0122 *u'v'* units reported in Smet's study [12] for memory color matching. The inter-observer variability was characterized by calculating the $\Delta u'_{10}v'_{10}$ across all the color samples and adapting conditions. Mean color difference of mean (MCDM) values in $u'v'$ unit of each adapting condition ranged from 0.0059 to 0.0105 with an average of 0.0078. The result was smaller than the 0.0162 $u'v'$ units reported in Smet's study [12], indicating that it might be easier for the observers to make haploscopic color matching than memory matching.

The intra- and inter- observer variations were also calculated using CIEDE2000. The mean value of intra-observer variations was 3.76 CIEDE2000 units. The inter-observer variations ranged from 2.94 to 4.91 CIEDE2000 units with an average of 3.58. The average values were substantially higher than the 1.8 and 1.9 CIEDE2000 units for intra- and inter-variability reported in Cho's study [13] for color matching under D65. This is due to the difference of adapting conditions and viewing techniques between the two experiments. Adapting conditions at 2700 and 6500 K were used in our study and the luminance levels of the reference and matching field were largely different in some conditions. The haploscopic matching setup used in this study restricted the observers' eye movements, which resulted in unnatural viewing conditions.

The averaged CIEDE2000 standard deviations (SDs) were calculated for each color sample under each adapting condition, as shown in Table 2. Adapting 1 refers to the condition when the left and right $L_w \approx 100$ cd/m^2; adapting 2 refers to the condition when the left $L_w \approx 100$ cd/m^2 and the right $L_w \approx 3000$ cd/m^2. It can be seen that the SDs across the four color samples under each adapting condition were smaller than 4 CIEDE2000 units. Note that 4 CIEDE2000 color difference units are comparable to the magnitude of 4 CMC (1:1) units which were found typical for inter-observer variation in chromatic adaptation studies [14]. The mean SD values were similar to the results in Cai's study [15] for color matching.

Table 2. The averaged CIEDE2000 standard deviations (SDs) for each color under each adapting condition.

	CCT = 2700 K		CCT = 6500 K	
Color	Adapting 1	Adapting 2	Adapting 1	Adapting 2
Red	1.20	1.68	2.04	1.47
Green	1.39	5.90	2.27	1.16
Blue	1.68	2.03	2.27	1.25
Yellow	0.84	1.81	2.02	2.33
Mean	1.28	2.86	2.15	1.55

Color matching results

Figure 2 shows the experimental results under each adapting condition on CIE 1976 $u'_{10}v'_{10}$ diagram. The average matched chromaticities are denoted with black circles and the reference colors are denoted with grey squares. The arrows show the color shift from the reference to the matched colors. When the luminance of the matching field increased, the matched colors generally shifted towards the illuminants. This indicates that higher luminance resulted in higher perceived colorfulness of the color samples. The distance between the matched colors and reference stimuli might be caused by the incompleteness of chromatic adaptation to the illuminants. To compare the chromatic adaptation degree under different CCTs, the matched chromaticities at 2700 K were transferred to those under 6500 K using CAT02 with $D = 1$, as shown in Fig. 3. It can be seen that the averaged matched chromaticities transferred from 2700 K generally shifted farther away from the reference stimuli. It suggests that the observers' chromatic adaptation degree to the illuminants at 6500 K was generally higher than the adaptation degree to the illuminants at 2700 K.

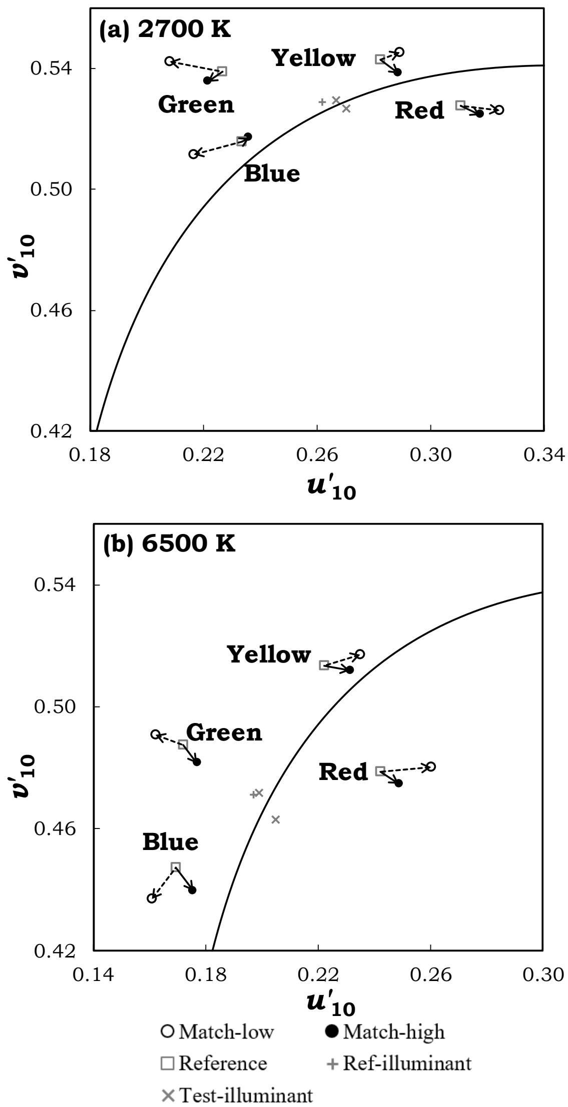

Figure 2. The average matched colors under the test illuminants and the reference stimuli under the reference illuminants at (a) 2700 K and (b) 6500 K on CIE 1976 $u'_{10}v'_{10}$ plane with CIE 1964 10° CMFs. The black line is the Planckian locus.

The color difference between the matched and reference colors in terms of $\Delta u'_{10}v'_{10}$ were computed for each color sample under each adapting condition, as shown in Fig. 4. The $\Delta u'_{10}v'_{10}$ for the color stimuli under all the adapting conditions ranged from 0.0075 to 0.0187 $u'v'$ units, with an average of 0.0128. This can be considered as small difference for the current purpose. The color difference was also calculated in terms of CIEDE2000, as shown in Table 3. The color difference under adapting 1 was slightly worse than the results reported in the past similar study [16]. The reasons might be that the adapting conditions in the reference and matching field were not identical and the viewing techniques were different. In Huang's study [16], the printed samples and the monitor for color matching were put in the same viewing booth and observers could look at them with both their eyes simultaneously. The color differences under adapting 2 were large. The large discrepancy was likely to be caused by the large difference between the luminance levels used in the matching and reference field.

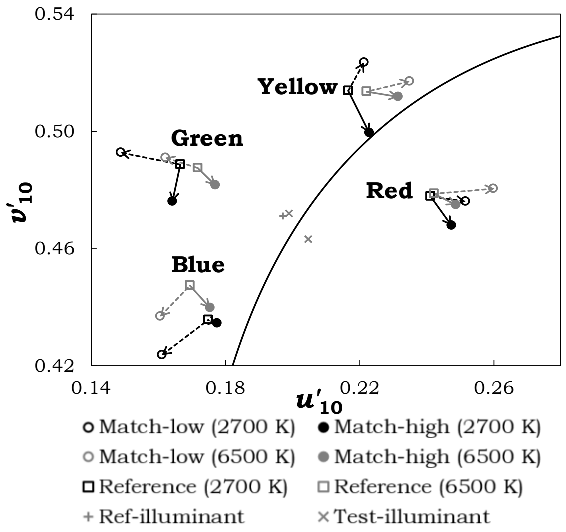

Figure 3. The averaged matched colors and reference samples under the illuminants at 6500K on CIE 1976 u'10v'10 plane with CIE 1964 10° CMFs. The chromaticities of the averaged matched colors and reference samples at 2700 K were transferred to those at 6500 K using CAT02 with D = 1.

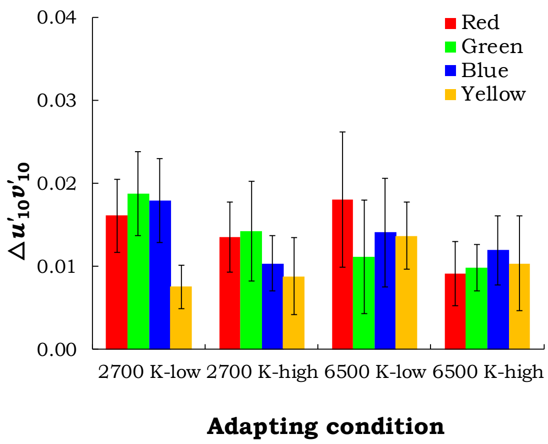

Figure 4. The color difference, together with the 95% confidence interval, between the matched colors and reference colors in terms of Δu'10v'10 with CIE 1964 10° CMFs for each color sample under each adapting condition.

Table 3. The mean color difference between the matched and reference colors in terms of CIEDE2000 for each color under each adapting condition.

	CCT = 2700 K		CCT = 6500 K	
Color	Adapting 1	Adapting 2	Adapting 1	Adapting 2
Red	3.93	13.41	3.00	13.50
Green	4.78	16.00	3.17	14.28
Blue	5.91	14.46	3.46	14.93
Yellow	4.92	16.02	4.76	14.79
Mean	4.89	14.97	3.59	14.38

Given the poor uniformity of CIE 1976 $u'_{10}v'_{10}$ diagram, the matched results under each adapting condition were transformed into the CAM02-UCS which includes the CAT02, as shown in Fig. 5. The transformation was made using the calculated D_c according to the equation from CAT02 [17]. According to the definition [18], the D_c depends on the luminance of adapting field. An 'average' surround condition was used in the experiment. The calculated $D_c \approx 0.89$ when $L_w \approx 100$ cd/m^2; and $D_c \approx 1$ when $L_w \approx 3000$ cd/m^2. It can be noticed that the luminance levels were carefully set to make the D_c close to 1 to minimize the effect of chromatic adaptation on color matching. According to the concept of chromatic adaptation, the chromaticities of the matched colors were supposed to be the same as the chromaticities of the reference stimuli. The existing distance between them was likely to be caused by the prediction error by the CAT02. The arrows represent the prediction error by CAT02. It indicates that CAT02 is not accurate in predicting these experimental results. The black arrows are generally longer than the grey arrows, indicating that the prediction error of CAT02 was larger at 2700 K.

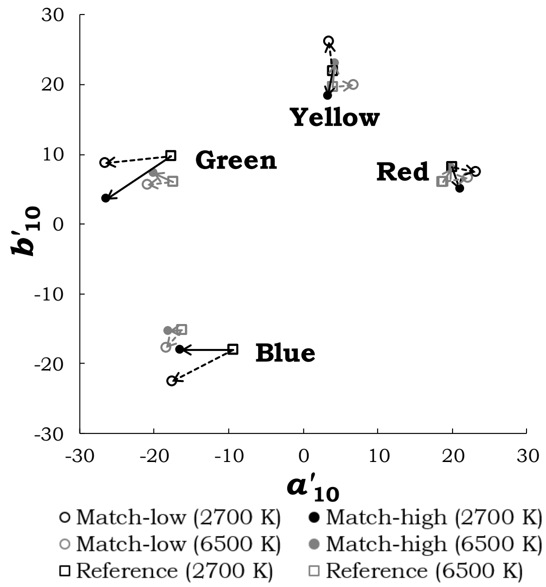

Figure 5. The average matched colors and reference samples under the test and reference illuminants transformed into CAM02-UCS using D_c.

The color difference between the matched and reference colors in terms of $\Delta a'_{10}b'_{10}$ was calculated with D_c for each color sample under each adapting condition, as shown in Fig. 6. Coupled with Fig 5, the prediction error by the CAT02 was generally larger at a lower CCT. It is likely that the prediction errors were caused by the over-estimation of the chromatic adaptation degree. This would further lead to the errors in predicting color appearance.

The effect of luminance on chromatic adaptation at different CCTs

In this experiment, the same stimulus at the reference field was matched under two different luminance levels. The matched colors were supposed to be identical. The color difference between the colors matched under low and high luminance was calculated in terms of $\Delta a'_{10}b'_{10}$ and $\Delta J'_{10}a'_{10}b'_{10}$ to assess the effect of luminance on chromatic adaptation at different CCTs, as shown in Fig. 7. The histograms show that the color difference caused by different luminance levels were significantly different at 2700 and 6500 K. Chromatic adaptation degrees under different luminance levels at 2700 K were largely different. It is clear that the change of luminance levels exerted a stronger effect on the observers' chromatic adaptation degree to the illuminants at a lower CCT.

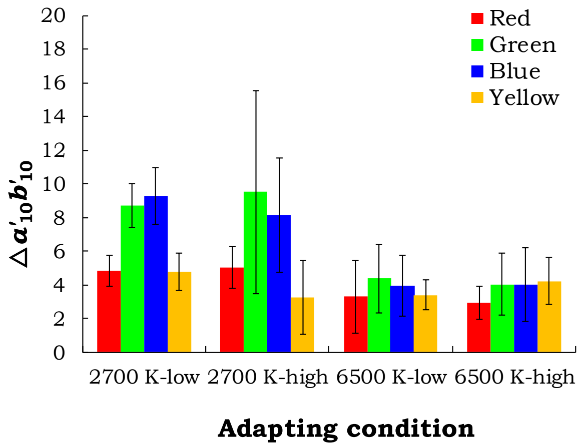

Figure 6. *The color difference, together with the 95% confidence interval, between the matched colors and reference color samples in terms of $\Delta a'_{10}b'_{10}$ with D_c under each adapting condition.*

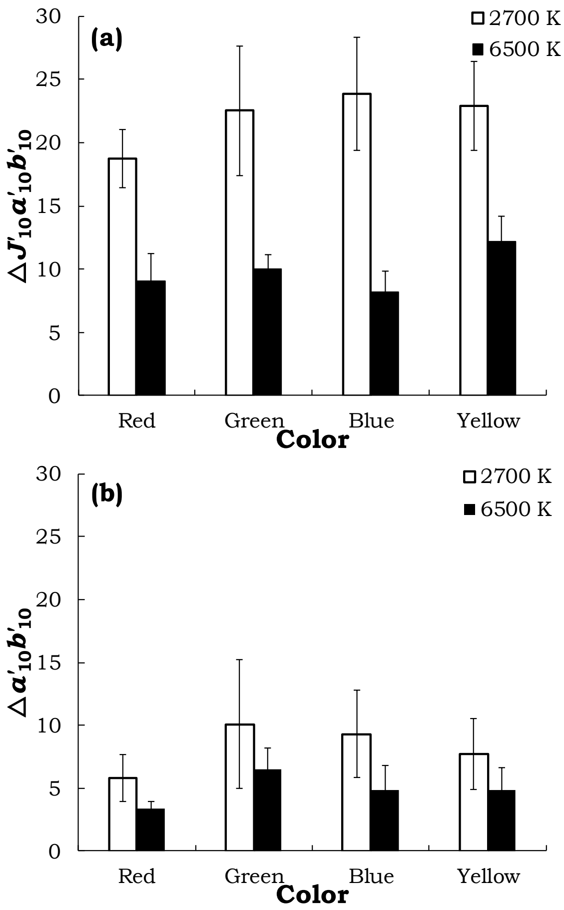

Figure 7. *The color difference, together with the 95% confidence interval, between the matched colors under low and high luminance in terms of (a) $\Delta J'_{10}a'_{10}b'_{10}$ and (b) $\Delta a'_{10}b'_{10}$.*

Testing color appearance models

The performance of color appearance models in predicting color appearance across different light levels was tested using the collected experimental data. The color attributes (i.e., lightness (*J*), brightness (*Q*), chroma (*C*), colorfulness (*M*), hue (*h*), and saturation (*s*)) of the reference stimuli and matched colors under each adapting condition were calculated using CIECAM02 and CAMHE (the revised model developed by Kim et al. [11]). Figure 8 compares the color appearance of the matched colors predicted by the two color appearance models. The arrows represent the change of the attributes when the luminance level in the matching field increased from 100 to 3000 cd/m^2. The same target under the same adapting condition was matched when the luminance increased. Therefore, the attributes of the matched colors were supposed to remain unchanged. Figure 8(a) indicates that the predicted lightness by CIECAM02 and CAMHE was smaller than the perceived lightness by the observers when the luminance level in the matching field increased. This result was consistent with the 'bending' effect found in Ou's study [10]. In addition, it can be seen that CAMHE performed better than CIECAM02 in predicting brightness and saturation. Both the two color appearance models characterize the cone response *V* using the Michaelis-Menten equation [19] (Eq. (1)). The parameter 'σ' was found to depend on the adapting luminance directly. A fixed σ is used in CIECAM02 while σ is allowed to vary according to the adaptation luminance in CAMHE. This may account for the improvement of CAMHE in predicting brightness and saturation. Both models performed well when predicting hue.

$$\frac{V}{V_m} = \frac{I^n}{I^n + \sigma^n} \qquad (1)$$

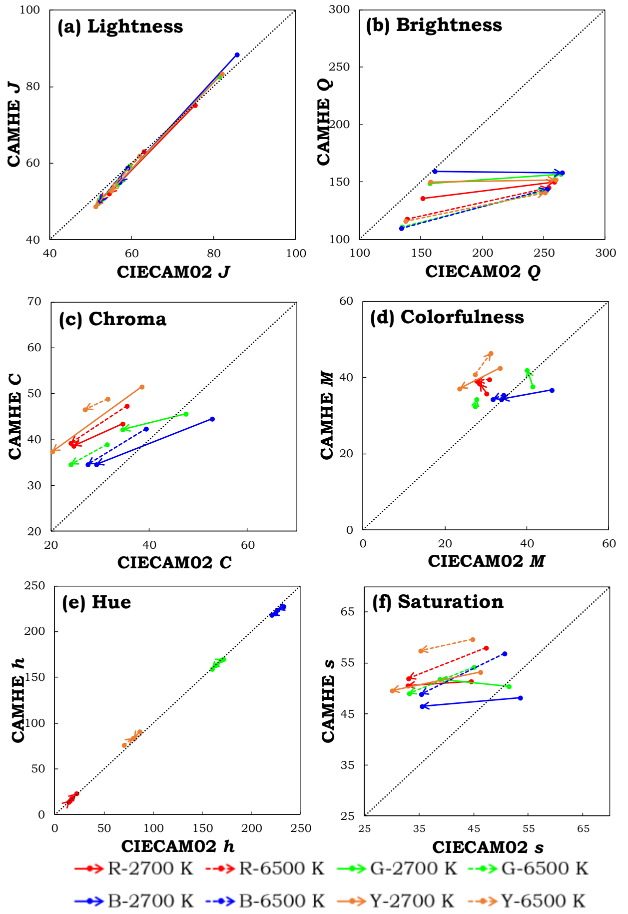

Figure 8. *Comparisons between the color appearance predicted by CIECAM02 and the color appearance predicted by CAMHE in terms of (a) lightness, (b) brightness, (c) chroma, (d) colorfulness, (e) hue, and (f) saturation.*

Conclusions

A visual experiment was carried out to collect corresponding color data under low photopic and very high light levels. Four color stimuli were matched under different luminance levels at 2700 and 6500 K. The reference L_w was set around 100 cd/m^2 while the two luminance levels were set for the matching field (i.e., $L_w \approx 100$ and 3000 cd/m^2). The visual results showed that higher luminance levels generally resulted in higher colorfulness. The effect of luminance on chromatic adaptation at different CCTs turned out to be different. The change of luminance levels exerted a stronger influence on the observers' chromatic adaptation degree to the illuminants at a lower CCT.

The performance of CIECAM02 was tested using the collected data. It turned out that CIECAM02 did not perform well in predicting lightness, brightness, and chroma at a very high light level. CAMHE was found to perform better than CIECAM02 in predicting brightness and saturation. One of the reasons is that CAMHE considers the effect of adapting luminance on the parameter σ when modeling the cone response. In addition, the prediction error of CAT02 was revealed, which was especially significant under illuminants at a lower CCT. Future experiments with high resolution in luminance levels are needed to further validate the findings in this study.

Funding

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