Research Article | Vol. 29, No. 24 / 22 Nov 2021 / Optics Express 40447

Optics EXPRESS

Effect of primary peak wavelength on color matching and color matching function performance

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Abstract: With the development of wide color gamut displays, several recent studies investigated the performance of the CIE standard color matching functions (CMFs) in characterizing the color matches and observer metamerism between different primary sets. These studies, however, always employed different primaries to produce color stimuli, which failed to isolate the effect of the peak wavelength from that of the spectral shape. In this study, we carefully selected primaries with similar spectral shapes but different peak wavelengths. Human observers adjusted the intensities of the seven matching primary sets to match the color appearance of six stimuli, with a field of view around 5.7° × 5.7°, produced using a reference primary set, which was the same as one of the matching primary sets. The results clearly revealed the significant effect of the primary peak wavelength, and the failure of using chromaticities to characterize color matches using different primaries. The CIE 2006 2° CMFs were found to have the best performance in characterizing the color matches on average among the four CIE standard CMFs (i.e., the CIE 1931 2°, CIE 1964 2°, CIE 2006 2°, and CIE 2006 10° CMFs), which did not support the CIE's recommendation of using the 10° CMFs for stimuli beyond 4°. When the two categorical observer CMFs (i.e., Sarkar 2 set and Beijing Institute of Graphic Communication "BIGC" 17 set) were considered together, the BIGC 17 set had the best performance on average. More importantly, the performance of the CMFs varied with the primary sets. When the matching and reference sets were the same, the performance of all the CMFs were consistently good. In contrast, when the blue or green primary, or both of the two primaries, was shifted, the performance of all the CMFs became much worse. This clearly implies the importance of considering primary wavelengths when specifying color matches using different CMFs.

1. Introduction

Color matching functions (CMFs) play a critical role in color science and management. They are used to specify how stimuli with different spectral compositions can match in color appearance. The set of CMFs, which was recommended by the International Commission on Illumination (CIE) in 1931, known as the CIE 1931 CMFs, is the most widely used set [1]. It was developed based on the two color matching experiments carried out by Wright [2,3] and Guild [4], in which human observers used monochromatic primaries at 460 nm, 530 nm, and 630 nm and broadband primaries respectively, to perform color matches for a 2° bipartite target. For practical use, the color matching data collected from these two experiments were transformed to an imaginary set of primaries, which was performed based on an assumption that the color matching data derived using different primary sets can be transformed between each other [5]. In 1964, another set of CMFs, known as the CIE 1964 10° CMFs, was recommended by the CIE [1]. It was derived based on the two color matching experiments carried out by Stiles and Burch [6] and Sperankaya [7] for stimuli with a 10° field of view (FOV), with the former using monochromatic primaries at 645.2 nm, 526.3 nm, and 444 nm and the latter using broadband primaries. These data were then

#438960 https://doi.org/10.1364/OE.438960
Journal © 2021 Received 27 Jul 2021; revised 1 Oct 2021; accepted 1 Oct 2021; published 18 Nov 2021

combined and transformed to derive the CIE 1964 10° CMFs. In order to derive CMFs that better correspond to the physiological mechanism of the human color vision (i.e., cone fundamentals), CIE established a technical committee in 1991. In 2006, the committee derived a model to estimate the cone fundamentals for normal observers with an FOV between 1° and 10° [8]. These cone fundamentals were also derived using the same primary set used by Stiles and Burch [6]. In 2015, the committee further proposed a method to transform these cone fundamentals to CMFs, and provided two sets of CMFs (i.e., CIE 2006 2° and 10° CMFs) for direct use [9].

In addition to these four sets of CIE standard CMFs, efforts have also been made to characterize the variations among human observers. In 2010, Sarkar proposed a categorical observer model, which classified human observers into eight categories with different CMFs (note: we refer to S1 to S8 CMF sets hereafter) [10]. Asano developed an individual colorimetric model for deriving the CMFs for individuals using different parameters [11]. In 2020, we performed a cluster analysis on the color matching data collected using seven devices with different primary sets, and proposed 19 categorical observer CMFs—BIGC1 to 19 (note: BIGC is an abbreviation for Beijing Institute of Graphic Communication, and BIGC1 to 19 were referred to B1 to B19 CMFs hereafter) [12].

Given the development of wide color gamut (WCG) display technologies, several recent color matching experiments have been carried out to compare the performance of the four CIE standard CMFs and the effect of primary set on color matches. For example, the human observers adjusted the intensities of the 16 primary sets produced using LEDs to match the color appearance of a white stimulus with an FOV of 3.8° produced by the LCD of an iPad in Hu et al [13]. The CIE 2006 2° CMFs were found to have the best performance. Li et al used a halogen lamp to produce a white reference stimulus with an FOV of 10° and asked the observers to perform color matches using eight LED primary sets [14]. The two CIE 10° CMFs were found to work similarly better than the two CIE 2° CMFs. Guo et al used an NEC-PA242W display to produce six reference stimuli with FOVs of 6° and the observers performed the color matches using four LED primary sets [15]. The CIE 1931 2° CMFs were found to have worse performance than the CIE 1964 10° and 2006 10° CMFs with the FOV modified to 6° following [9]. Wu et al used an LCD smartphone display to produce seven reference stimuli with FOVs of 4.77° and the observers performed the color matches using four OLED displays, with the CIE 2006 2° CMFs being found to have the best performance [16]. It was clear that these studies did not have consistent results in comparing the performance of the four CIE standard CMFs. Moreover, it can be observed that these studies always used different equipment to produce the reference and matching stimuli, and the spectral shapes of the primary sets were different. Therefore, the effect of the primary wavelength was confounded with that of the spectral shape.

In this study, we carefully selected the primaries, so that the effect of the peak wavelength can be isolated. Both the reference and matching stimuli were produced using primaries with similar spectral shapes but different peak wavelengths. The observers adjusted the intensities of seven primary sets to match the color appearance of six color stimuli produced by a reference primary set. The seven primary sets included six sets that had one or two different primaries as the reference set and one set that was identical to the reference set. In addition to the four CIE standard CMFs, we also investigated the performance of two categorical observers CMFs—S2 and B17, which were found to have the best performance among the Sarkar and BIGC categorical observer CMF sets in characterizing the color matches using pairs of surface colors for the young observers (i.e., between 19 and 25 years of age) in our previous work [12].

2. Methods

2.1. Apparatus

Two six-channel LED panels were used to produce color stimuli, with the LED channels used as the primaries. Figure 1 shows the spectral power distributions (SPDs) of the six primaries,

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including two sets of red (R1 and R2), green (G1 and G2), and blue (B1 and B2), measured using a calibrated PhotoResearch PR-655 spectroradiometer; Table 1 summarizes the colorimetric characteristics derived from the measured SPDs. These primaries were carefully selected, with the two sets having very similar full-width-half-maximum (FWHM) values but different peak wavelengths, so that the effect of the peak wavelength can be isolated. It can be noticed that the two primaries in the blue and green sets had differences around 20 nm, while the two in the red set had a difference around 40 nm. It is worthwhile to mention that though the FWHM values of the two green primaries were a little wider than those of the other primaries, we mainly focused on the effect of the peak wavelength in this study. In addition, slightly wider FWHM values are common for green primaries.

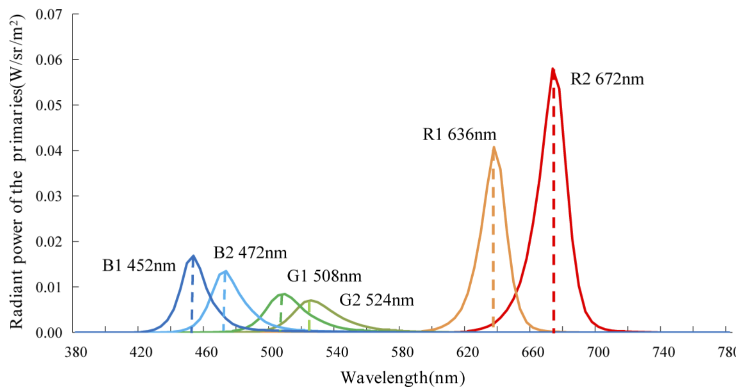

Fig. 1. Spectral power distributions (SPDs) of the primaries measured using a PhotoResearch PR-655 spectroradiometer.

Table 1. Colorimetric characteristics of the primaries (note: x_{10}, y_{10}, u'_{10}, and v'_{10} were calculated using the CIE 1964 10° CMFs).

Primary	Peak wavelength (nm)	FWHM (nm)	x_{10}	y_{10}	u'_{10}	v'_{10}
R1	636	20	0.694	0.306	0.525	0.521
R2	672	20	0.714	0.286	0.572	0.514
G1	508	28	0.116	0.705	0.041	0.565
G2	524	32	0.236	0.719	0.085	0.580
B1	452	20	0.146	0.064	0.168	0.165
B2	472	21	0.111	0.170	0.092	0.318

The light emitting area of the LED panel was 5 cm × 5 cm. A black frame, with a 4 cm × 4 cm opening, was used to cover each LED panel, with the actual emitting area perceived by the observer being 4 cm × 4 cm. The LED panel had a good uniformity based on the measurements we took in our past experiments. For this experiment, we used the above six primaries to produce a stimulus which had the same chromaticities as the CIE D50 illuminant, as measured at the center of the emitting area. The chromaticities measured at the four corners had a mean color difference from the mean (MCDM) values of 0.0013 units of $u'_{10}v'_{10}$. The stability of the emitting area was also verified by measuring the chromaticity shift of the same stimulus (i.e., the one having the same chromaticities as D50) at the center of the emitting area every two minutes from 5 to 300 minutes after the LED panel was switched on. The chromaticity shifts were smaller than 0.0011 units of $u'_{10}v'_{10}$. Thus, the uniformity and stability of the LED panels were reliable for the experiment.

The intensity of each primary was allowed to be adjusted from 0 to 100%, with a step of 0.1%, using a remote-control panel. The color shift introduced by a step of adjustment for each primary was between 0.0001 to 0.0008 units of $u'_{10}v'_{10}$ (~ 0.03 to 0.21 ΔE^*_{ab}), which was much smaller than one unit of just-noticeable color difference (JND) [17].

2.2. Color stimuli and primary sets

One LED panel was used as a reference panel to produce reference stimuli using three primaries (i.e., R1, G2, and B1) having the peak wavelengths of 636 nm, 524 nm, and 452 nm. These three primaries were the same as those used in our previous work [15] and the peak wavelengths were generally similar to those used in Stiles and Burch (i.e., 645.2 nm, 526.3 nm, and 444.4 nm) [6], with the wavelength shifts below 10 nm, which were found to introduce a small degree of observer metamerism. The human observers adjusted the intensities of one or two primaries in the other LED panel, with a total of seven primary sets (i.e., L1 to L7), to match the color appearance of the stimulus shown on the reference panel. Table 2 summarizes the primary sets and the primaries that were shifted to be adjusted, together with the color gamut areas enclosed by the primary sets; Fig. 2 shows the color gamut in the CIE 1976 $u'v'$ chromaticity diagram. In particular, L1 set was the same as the primary set used in the reference panel, which was designed to evaluate the accuracy and reliability of the experiment, and also the performance of various CMFs.

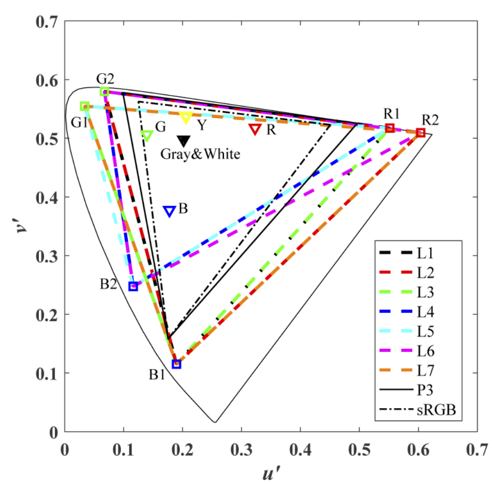

Fig. 2. Color gamuts enclosed by the seven primary sets, together with sRGB and P3, in the CIE 1976 $u'v'$ chromaticity diagram. (note: since both sRGB and P3 are specified using the CIE 1931 2° CMFs, this figure is plotted using the same CMFs for allowing a better comparison).

Five color stimuli (i.e., grey, red, yellow, green, and blue), which were recommended by the CIE for evaluating the uniformity of color spaces and the performance of color difference formulas [18], and a white stimulus, were produced and calibrated on the reference panel as the reference stimuli for color matching, as shown in Fig. 2. Table 3 summarizes the colorimetric characteristics of these six reference stimuli, as measured using the spectroradiometer on the reference panel.

2.3. Observers

Seventy naïve human observers (35 males and 35 females) between 19 and 24 years of age (mean = 21.5, std. dev. = 1.5) were recruited for the experiment. All the observers had normal

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Table 2. Summary of the primary sets.

Primary sets	Shifted primaries	Color gamut area	
		CIE 1964 $x_{10}y_{10}$ chromaticity diagram	CIE 1976 $u'_{10}v'_{10}$ chromaticity diagram
L1(R1-G2-B1)	-	0.1697	0.0878
L2(R2-G2-B1)	R2	0.1773	0.0956
L3(R1-G1-B1)	G1	0.1766	0.0947
L4(R1-G2-B2)	B2	0.1533	0.0572
L5(R1-G1-B2)	G1 and B2	0.1530	0.0600
L6(R2-G2-B2)	R2 and B2	0.1602	0.0624
L7(R2-G1-B1)	R2 and G1	0.1827	0.1021

Table 3. Colorimetric characteristics of the six reference stimuli shown on the reference panel, as calculated using the CIE 1964 10° CMFs.

Stimulus	x_{10}	y_{10}	u'_{10}	v'_{10}	Y_{10}
White	0.348	0.380	0.202	0.498	102.0
Grey	0.347	0.379	0.202	0.498	30.9
Red	0.507	0.372	0.315	0.519	14.1
Yellow	0.405	0.464	0.209	0.538	71.4
Green	0.277	0.423	0.147	0.506	24.2
Blue	0.226	0.223	0.174	0.384	8.1

color vision, as tested using the Ishihara Color Vision Test. All the observers participated in similar color matching experiments before, but none of them had an idea about the objective of this study.

2.4. Experimental procedures

Upon arrival, the observer completed a general information form, and the Ishihara Color Vision Test, and then was seated 40 cm in front of the LED panels, with the illumination in the experiment space switched off. The two LED panels were placed side by side, with a distance of 5 cm between the inner edges of the two stimuli. The observer was seated to align his or her sagittal plane to the center between the two LED stimuli, so that each stimulus occupied an FOV around $5.7^\circ \times 5.7^\circ$. Figure 3 shows a photograph taken from the observer's eye position. The experimenter instructed the observer how to use the control panel to adjust the color appearance of the stimulus shown on the right panel to match that of the stimulus shown on the left panel, and the observer completed three practice trials to get familiar with the adjustments. In particular, the adjustment was always started from black (i.e., the right panel was started from black) using the control panel, with a step of 0.1% of the maximum intensity of each channel. Then, the experiment began with the first color match. The order of the color stimuli and the order of the primary sets were randomized. The observer was allowed to take as much time as he or she needed, until he or she was satisfied with the match, and each color match took around five to eight minutes. Considering the length of the experiment, the color match for the white stimulus using each primary set was performed by 39 observers, with 12 observers making a repeated match for evaluating the intra-observer variations; the color match for each of the other five stimuli using each primary set was performed by 41 observers, with 10 observers making a repeated match for evaluating the intra-observer variations. In total, each stimulus was matched by 51 times, with a total of 2142 color matches (51 observations $\times$ 6 stimuli $\times$ 7 primary sets) in the experiment.

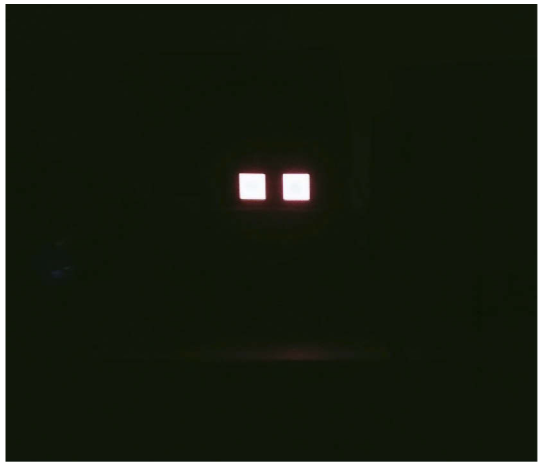

Fig. 3. Photograph of the light stimuli viewed by the observer during the experiment, which was captured from the observer's eye position.

3. Results and discussions

The SPDs of the stimuli that were adjusted by the observers for creating the color matches were measured after the experiment using the spectroradiometer from the observer's eye position. These SPDs were used for the following analyses.

3.1. Intra- and inter-observer variations

The intra- and inter-observer variations were characterized using the MCDM values in the CIE 1976 $u'_{10}v'_{10}$ chromaticity diagram. Specifically, the intra-observer variations were characterized using the chromaticity difference $\Delta u'_{10}v'_{10}$ between the chromaticities of the stimuli that were repeatedly adjusted by each observer; the inter-observer variations were characterized using the chromaticity difference $\Delta u'_{10}v'_{10}$ between the chromaticities of the stimuli adjusted by each of the 51 observations and the average chromaticities of the stimuli adjusted by the 51 observations (i.e., an average observer). The MCDM values of the intra-observer variations ranged between 0.0019 and 0.0029, with a mean of 0.0024; the MCDM values of the inter-observer variations ranged between 0.0040 and 0.0069, with a mean of 0.0059. Table 4 summarizes the minimum, maximum, and mean of the MCDM values for each primary set. These MCDM values were generally comparable to several recent color matching experiments [13,14,16], suggesting the reliability of the experiment. In addition, the intra-observer variations were generally smaller than 0.004 $u'_{10}v'_{10}$ units (i.e., $\approx$ 1 just-noticeable color difference, JND) [17].

It can be observed that the average inter-observer variations were generally larger than the average intra-observer variations, regardless of the primary sets. In addition, L1 set having the same primaries as the reference panel, had the smallest inter-observer variations, which was consistent to our previous work [15].

3.2. Performance of the CIE standard CMFs

The chromaticities of the reference stimuli and the stimuli adjusted by the observers were calculated using the four CIE standard CMFs, including CIE 1931 2°, CIE 1964 10°, CIE 2006

Table 4. Intra- and inter-observer variations characterized using the MCDM values in the CIE 1976 $u'_{10}v'_{10}$ chromaticity diagram.

		L1	L2	L3	L4	L5	L6	L7
Intra-	Min	0.0002	0.0002	0.0003	0.0001	0.0002	0.0002	0.0004
	Max	0.0061	0.0046	0.0109	0.0111	0.0123	0.0123	0.0097
	Mean	0.0021	0.0019	0.0027	0.0025	0.0026	0.0024	0.0029
Inter-	Min	0.0001	0.0004	0.0005	0.0001	0.0004	0.0001	0.0003
	Max	0.0142	0.0305	0.0227	0.0225	0.0419	0.0226	0.0214
	Mean	0.0040	0.0059	0.0055	0.0059	0.0069	0.0064	0.0068

2°, and CIE 2006 10° CMFs (note: the 2006 10° CMFs were derived by setting the age to 22, which was the average age of the observers, following the method in CIE 170-1:2006 [8]).

Figures 4 and 5 show the chromaticities of the reference stimuli and the average chromaticities of the stimuli adjusted by the observers calculated using the 2° and 10° CMFs respectively, with the chromaticity difference $\Delta u'_{10}v'_{10}$ values summarized in Fig. 6. It can be observed from Figs. 4 and 5 that the blue stimulus always had the largest color differences between the reference and matched stimuli.

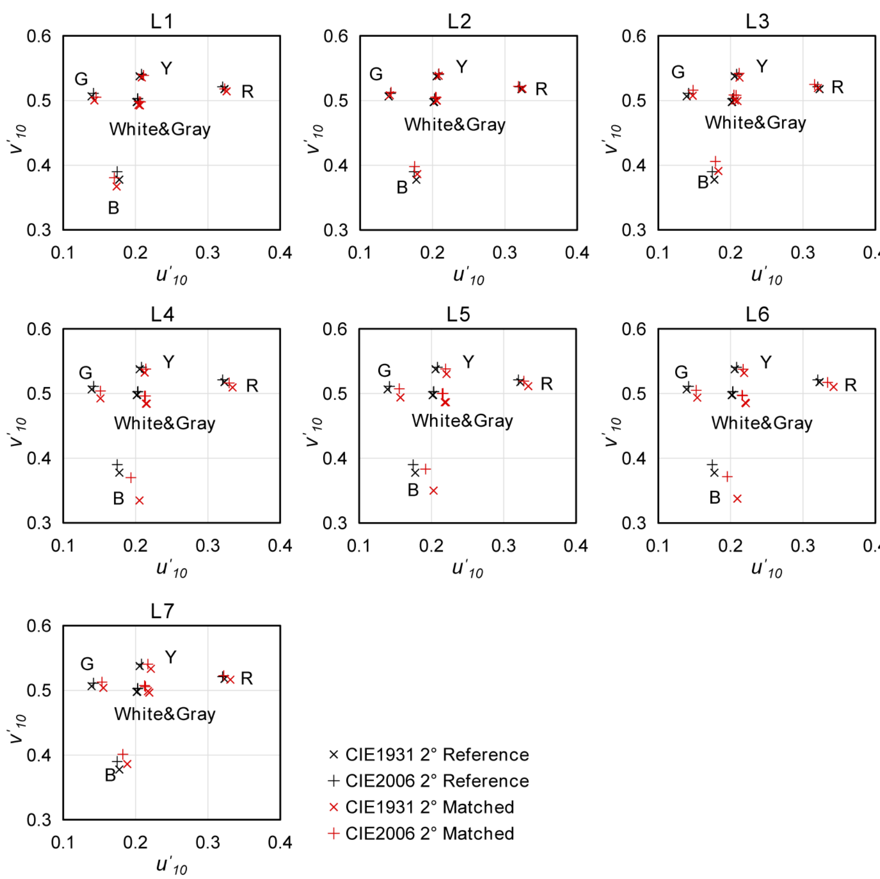

Fig. 4. Chromaticities of the reference stimuli and the average chromaticities of the stimuli adjusted by the observers, calculated using the CIE 1931 and 2006 2° CMFs.

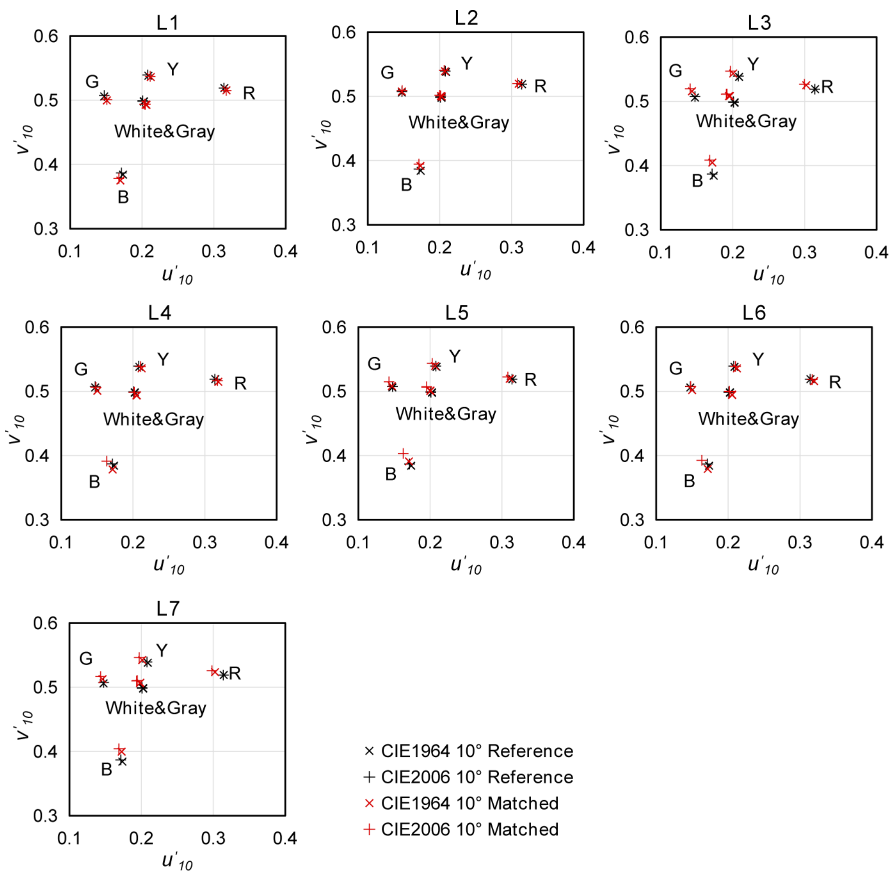

Fig. 5. Chromaticities of the reference stimuli and the average chromaticities of the stimuli adjusted by the observers, calculated using the CIE 1964 and 2006 10° CMFs.

The performance of the CMFs in response to the primary shifts merit further comparisons. The chromaticity differences were the smallest when the color matches were performed using L1 set, with the average chromaticity differences being slightly greater than 0.004, regardless of the CMFs, since the reference panel used the exactly same primary set. It was interesting to see that the red stimulus always had much larger chromaticity differences.

For the other six primary sets, the average chromaticity difference was the largest when both the blue and green primaries were shifted (i.e., L5 set), and was the smallest when only the red primary was shifted (i.e., L2 set). More specifically, the shift of the primary affected the individual color stimuli. The shift of the blue primary in L4, L5, and L6 sets caused larger chromaticity differences to the blue stimulus, especially when the CIE 1931 2°, 1964 10°, and 2006 10° CMFs were used; the shift of the green primary in L3, L5, and L7 sets caused larger chromaticity differences to the green stimulus. In contrast, the shift of the red primary in L2, L6, and L7 did not cause larger chromaticity differences to the red stimulus in comparison to the other primary sets. However, it was interesting to see that the chromaticity differences of the red stimuli in L2, L6, and L7 calculated using the two 2° CMFs were always greater than those calculated using the two 10° CMFs, which may need to be further investigated. When the CIE 2006 2° CMFs were used, the red stimuli in L2, L6, and L7 and the blue stimuli in L4, L5, and L6 had comparable color differences, as shown in Fig. 6(c). Interestingly, though there was no yellow primary, the chromaticity differences for the yellow stimulus were greater when the green

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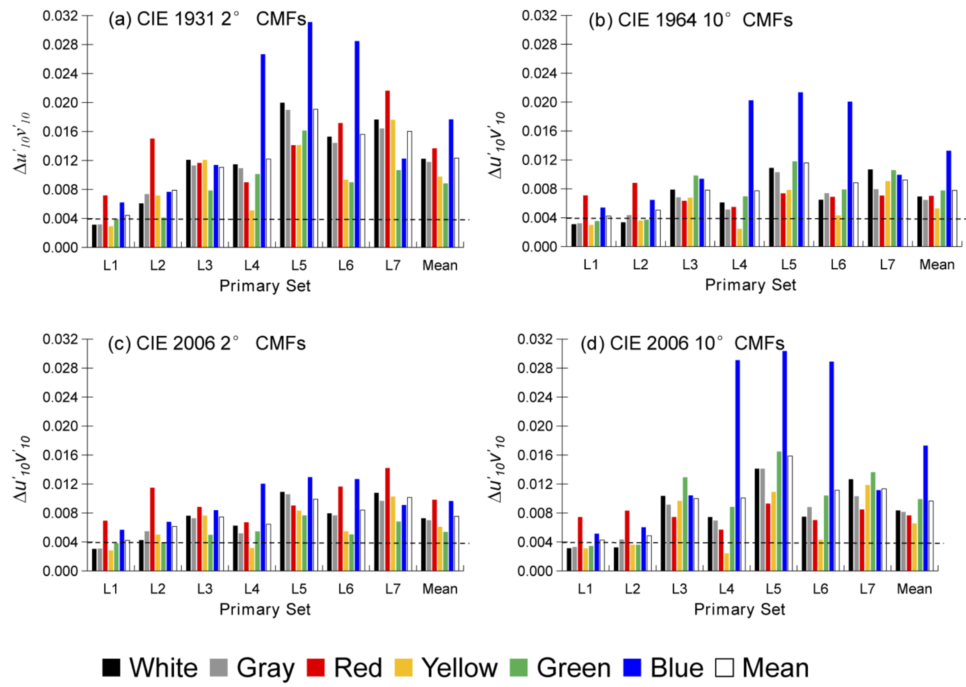

Fig. 6. Chromaticity differences $\Delta u'_{10}v'_{10}$ between the average chromaticities of the stimuli adjusted by the observers using the seven primary sets and the chromaticities of the reference stimuli shown on the reference panel calculated using the four CMFs. (a) CIE 1931 2° CMFs; (b) CIE 1964 10° CMFs; (c) CIE 2006 2° CMFs; (d) CIE 2006 10° CMFs.

primary was shifted (i.e., L3, L5, and L7). For the neutral color stimuli (i.e., white and gray), the chromaticity differences were generally larger when the green primary was shifted in L3, L5, and L7 sets.

The 95% confidence ellipses of the chromaticities adjusted by the observers, which were calculated using the four CMFs, are shown in Fig. 7, with the ellipse areas summarized in Fig. 8. A larger ellipse suggests a larger observer variation and a greater degree of observer metamerism. When the L1 set was used, the ellipses derived using the four CMFs generally overlapped, with the similar sizes and orientations. It was also interesting to see that the red stimulus had the largest ellipse areas. This, together with the largest chromaticity differences shown in Fig. 6, seemed to suggest that the observers were less sensitive to the color differences in the red region in the chromaticity diagram. Of course, this could be due to the nonuniformity of the CIE 1976 chromaticity diagram. For the other six primary sets, though the four ellipses did not always overlap, which was due to the shifts of the chromaticities of the stimuli shown on the reference panel, as shown in Figs. 4 and 5, the sizes and orientations of the ellipses were generally similar, illustrating the similar degrees of observer metamerism characterized using the four CMF sets. On average, L1 set introduced the smallest degree of observer metamerism, while L5 set introduced the greatest degree of observer metamerism. For the six color stimuli, the blue stimulus had the largest observer metamerism, while the yellow stimulus had the smallest among the six colors. When the blue primary was shifted in L4, L5, and L6, the observer metamerism on the blue stimulus became extremely large.

The shift of the primaries also changed the orientations of the ellipses. Specifically, shifting the blue primary from B1 to B2 (i.e., L4, L5, and L6) increased the size and changed the orientation of the ellipse of the blue stimulus; shifting the green primary from G2 to G1 (i.e., L3, L5, and L7)

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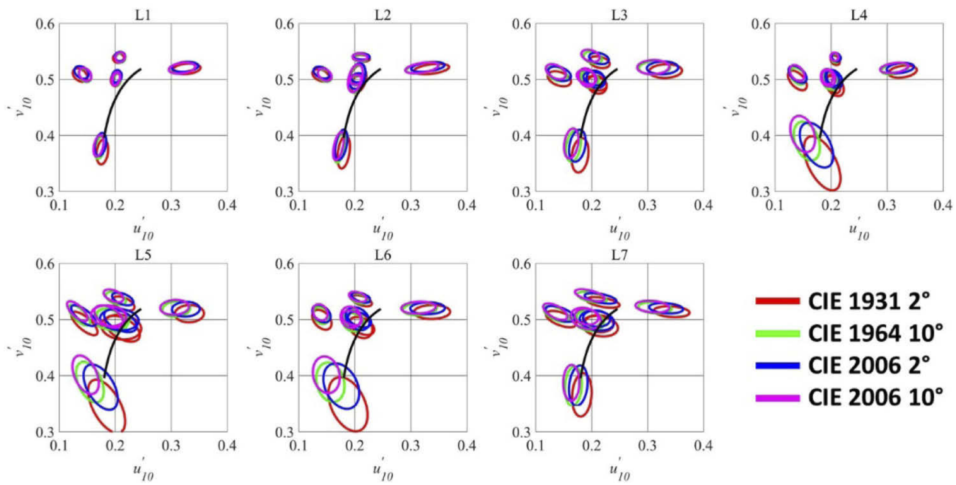

Fig. 7. 95% confidence error ellipses fitted based on the chromaticities of the stimuli adjusted by the observers using the seven primary sets, as calculated using the four CIE CMFs.

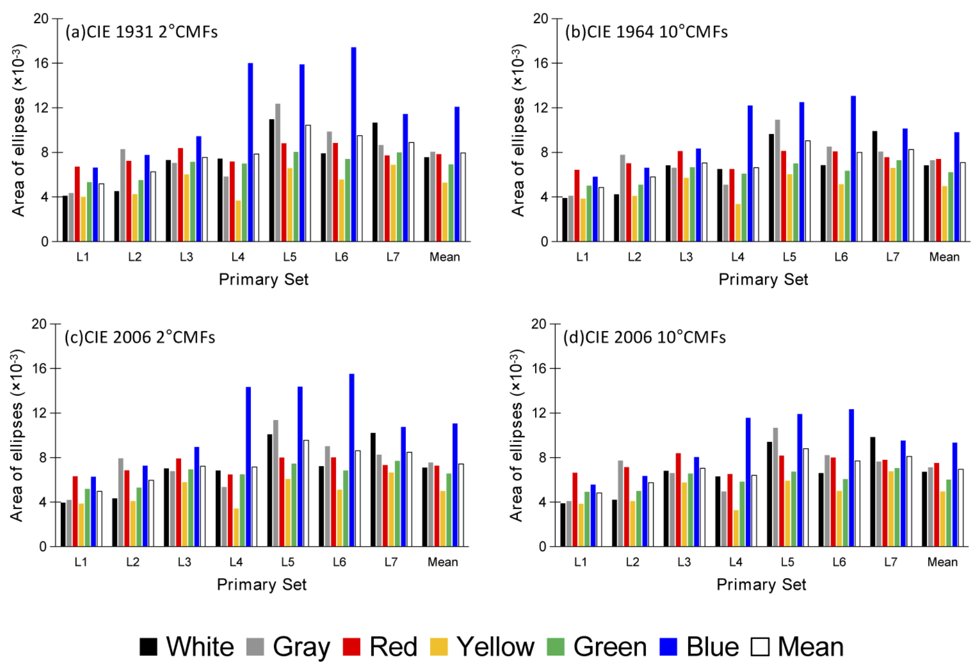

Fig. 8. Areas of the 95% confidence error ellipses fitted based on the chromaticities of the stimuli adjusted by the observers using the seven primary sets, as calculated using the four CIE CMFs.

increased the size and changed the orientation of the ellipse of the green stimulus. In contrast, shifting the red primary from R1 to R2 (i.e., L2, L6, and L7) did not cause significant changes, in terms of size and orientation, to the ellipse of the red stimulus. For the neutral colors (i.e., white and gray), the most significant increase of the ellipse size happened to the L5 and L7 primary sets, both of which shifted the green primary from G2 to G1.

3.3. Performance of categorical observer CMFs

As mentioned in Section 1, our previous study found that the categorical observer CMFs had better performance than the CIE standard CMFs in characterizing the color matches using different primary sets, which may suggest that these categorical observer CMFs can better represent the observers in certain categories. Therefore, we used two best categorical observer CMFs for the young observers—S2 in Sarkar's model and B17 in BIGC model, as we show in Table 1to characterize the color matches in this experiment.

Figure 9 shows these two categorical observer CMFs and the four CIE standard CMFs; Table 5 summarizes and compares the parameters of these CMFs, in terms of the peak wavelength, FWHM, and maximum spectral tristimulus values (STV_{max}). It can be observed that these CMFs have significant differences in the $\bar{x}(\lambda)$ and $\bar{z}(\lambda)$ functions, in terms of the peak response (i.e., STV_{max}), and also in the $\bar{y}(\lambda)$, in terms of the FWHM. In particular, for the $\bar{x}(\lambda)$, the S2 CMFs have the greatest response; for the $\bar{z}(\lambda)$, the CIE 2006 10° and B17 have the greatest responses; for the $\bar{y}(\lambda)$, the CIE2006, S2, and B17 CMFs had the greatest FWHM values.

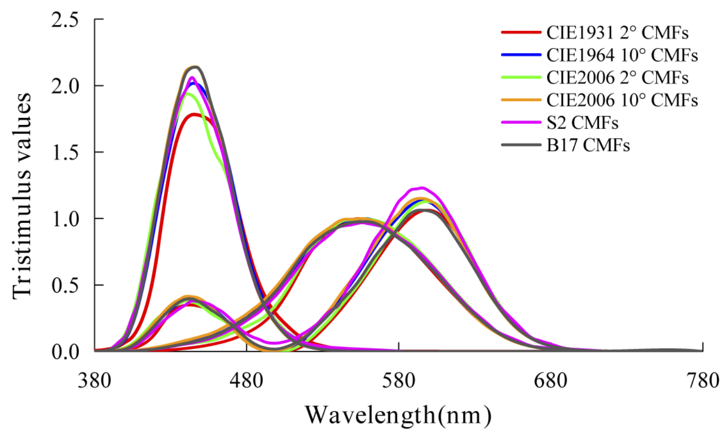

Fig. 9. Four CIE standard CMFs and two categorical observer CMFs.

Figure 10 shows the chromaticity differences between the reference stimuli and the average stimuli adjusted by the observers using the seven primary sets, which were calculated using the two categorical CMFs described above. It can be noticed that the B17 CMFs had relatively poor performance in characterizing the color matches of the blue stimulus, especially when the primary sets contained a different blue channel from the reference panel (i.e., L4, L5, and L6 contained B2, while the reference panel contained B1).

3.4. Comparison among the six CMFs and the seven primary sets

Table 6 summarizes the average chromaticity differences $\Delta u'_{10}v'_{10}$ of the six color stimuli for each primary set and the average chromaticity differences across the seven primary sets using the six CMFs, with the CMFs resulting the smallest $\Delta u'_{10}v'_{10}$ for each primary set underlined. On average, the B17 CMFs had the best performance. The different primary sets, however, resulted in different performance of the CMFs. Only when the red primary was changed, the

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Table 5. Summary of the parameters of the six CMFs.

CMFs		Peak wavelength	Half-max wavelength		FWHM	STV_{max}
CIE 1931 2°	$\bar{x}(\lambda)$	599	556	635	79	1.062
		442	423	472	49	0.350
	$\bar{y}(\lambda)$	555	510	610	100	1.000
	$\bar{z}(\lambda)$	446	423	478	55	1.782
CIE 1964 10°	$\bar{x}(\lambda)$	596	552	634	82	1.132
		442	419	470	51	0.387
	$\bar{y}(\lambda)$	557	503	612	109	0.999
	$\bar{z}(\lambda)$	445	420	476	56	2.018
CIE 2006 2°	$\bar{x}(\lambda)$	599	557	636	79	1.1277
		441	417	469	52	0.381
	$\bar{y}(\lambda)$	556	508	613	105	0.999
	$\bar{z}(\lambda)$	441	418	475	57	1.945
CIE2006 10°	$\bar{x}(\lambda)$	594	551	632	81	1.152
		441	419	468	49	0.420
	$\bar{y}(\lambda)$	556	500	611	111	1.000
	$\bar{z}(\lambda)$	446	420	473	53	2.147
S2	$\bar{x}(\lambda)$	595	554	633	79	1.229
		445	422	474	52	0.381
	$\bar{y}(\lambda)$	556	504	614	110	0.969
	$\bar{z}(\lambda)$	444	420	473	53	2.060
B17	$\bar{x}(\lambda)$	595	554	635	81	1.063
		443	420	470	50	0.396
	$\bar{y}(\lambda)$	558	502	612	110	0.976
	$\bar{z}(\lambda)$	446	420	474	54	2.140

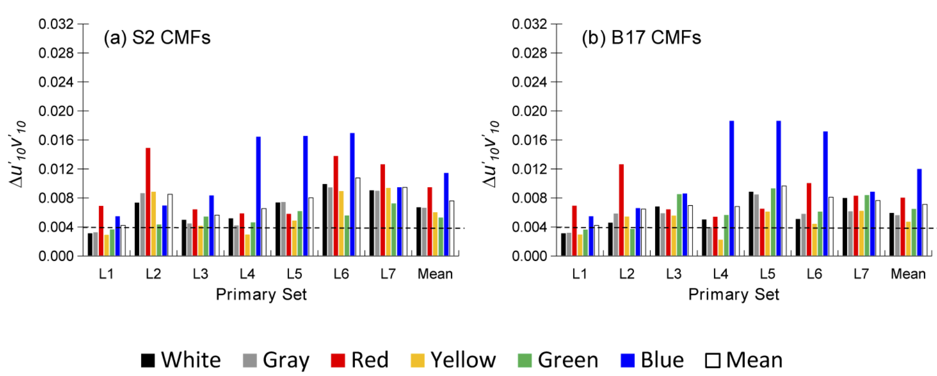

Fig. 10. Chromaticity differences $\Delta u'_{10}v'_{10}$ between the average chromaticities of the stimuli adjusted by the observers using the seven primary sets and the chromaticities of the reference stimuli shown on the reference panel calculated using the two categorical observer CMFs. (a) S2; (b) B17.

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smallest chromaticity difference happened to one of the CIE standard CMFs (i.e., the CIE 2006 10° CMFs). For the other primary sets, either the S2 or B17 CMFs had the smallest chromaticity differences. When the blue or green primary, or both of them, was changed, the S2 CMFs had the best performance. This clearly suggests that the CIE standard CMFs may not be the optimal sets of CMFs for industry applications. In addition, when both the reference and matching stimuli employed the same primary set (i.e., L1 vs reference), CMFs seemed not matter, as all the six CMFs resulted in very similar $\Delta u'_{10}v'_{10}$ values, all of which were the smallest among all the seven sets.

Table 6. Average chromaticity differences of between the reference stimuli and the average stimuli adjusted by the observers for the six color stimuli using the six CMFs, with the smallest value for each primary set underlined.

CMFs		L1	L2	L3	L4	L5	L6	L7	Mean
CIE standard CMFs	CIE 1931 2°	0.0044	0.0079	0.0111	0.0122	0.0191	0.0156	0.0160	0.0123
	CIE 1964 10°	0.0042	0.0051	0.0078	0.0077	0.0116	0.0088	0.0092	0.0078
	CIE 2006 2°	0.0042	0.0062	0.0075	0.0065	0.0099	0.0084	0.0101	0.0075
	CIE 2006 10°	0.0043	**0.0049**	0.0100	0.0101	0.0159	0.0112	0.0113	0.0097
Categorical Observer CMFs	S2	0.0042	0.0085	**0.0055**	**0.0060**	**0.0073**	0.0103	0.0093	0.0073
	B17	0.0042	0.0065	0.0070	0.0068	0.0096	**0.0081**	**0.0076**	**0.0071**
Mean		0.0043	0.0063	0.0082	0.0082	0.0122	0.0104	0.0106	0.0086

Furthermore, in addition to comparing the chromaticity differences, we further compared the chromaticity differences between the reference stimuli and the stimuli adjusted by each observer using the six CMFs, and assigned the CMFs resulting the smallest chromaticity differences to represent each observer. Figure 11 summarizes the frequencies that each set of CMFs resulted in the smallest chromaticity differences among the 51 observers. When only the red primary was shifted (i.e., L2), the CIE 2006 10° CMFs had the best performance. When the green primary was shifted (i.e., L3 and L5), S2 CMFs had the best performance. These generally corroborated the results of average the chromaticity differences, as summarized in Table 6.

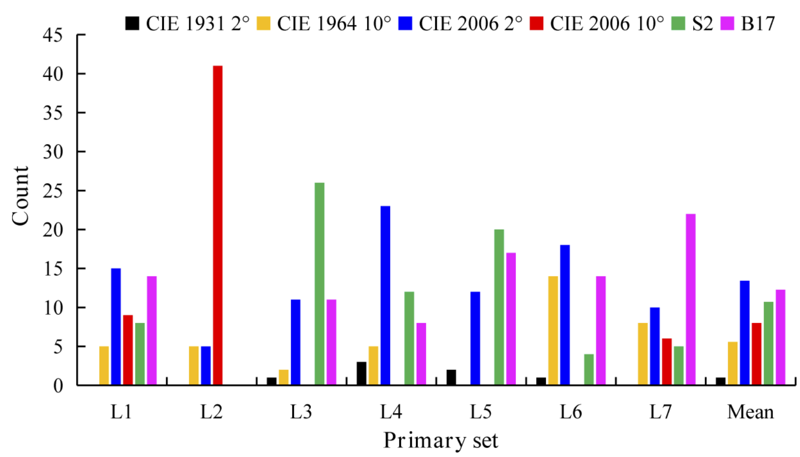

Fig. 11. Frequencies of the six CMFs that resulted in the smallest chromaticity difference for each individual observer when using the seven primary sets.

CMFs are used to characterize the color matching mechanisms in the human visual system. For example, the CIE 2006 CMFs are generally linear transformations of the cone fundamentals of human observers of different visual conditions for different sizes of FOV. Therefore, the performance of CMFs is expected to be independent from the spectral compositions of color stimuli. This also applies to the categorical observer CMFs, which were developed to characterize the color matching mechanisms of different categories of the human observers. The results presented in this study, however, clearly showed the significant effect of the spectral composition of primaries, especially the peak wavelength, as no CMFs always worked best for all the primary sets. This seems to suggest that different CMFs are need for calibrating and characterizing color matches when different primary sets are used.

In this experiment, the shift of the blue primary from B1 to B2 (i.e., in L4, L5, and L6) introduced the most serious problems to the CMFs, in terms of characterizing color matches, especially to the blue stimulus. Interestingly, such findings seemed to support Thornton's prime color theory [19,20], though this study was not designed to test the theory. When the blue primary was shifted, the shift happened from the "prime color" region towards the "anti-prime color" region. In contrast, the shifts of the other two primaries did not introduce a significant effect, which could be due to the fact that the shifts did not happen in the "prime color" region. It is worthwhile to carry out further experiments to directly test the prime color theory. In short, with the easier adjustments of the primaries in lighting and display systems, it is necessary to further explore the performance of different CMFs for different primary sets, so that consistent color appearance can be achieved using different primary sets.

4. Conclusion

A color matching experiment was carried out to investigate how the peak wavelengths of primaries affected the performance of the various CMFs, including the CIE standard CMFs and categorical observer CMFs. In particular, the spectral shapes of the primaries were fixed, so that the effect of the primary wavelength was isolated. Seventy observers adjusted the intensities of seven primary sets (i.e., L1 to L7) to match the color appearance of six stimuli, with an FOV around $5.7° \times 5.7°$, produced using one primary set (i.e., L1). The six primary sets (i.e., L2 to L7) had either one or two primaries different from the L1 primary set.

The results clearly revealed that the same chromaticities derived using a certain CMF set did not always predict the color matches if different primary peak wavelengths were used. On average, the CIE 2006 2° CMFs had the best performance when characterizing the color matches, among the four CIE standard CMFs (i.e., the CIE 1931 2°, 1964 10°, 2006 2°, and 2006 10° CMFs), especially to the blue stimulus. Such a result did not support the CIE's recommendation of using 10° CMFs for stimuli with an FOV beyond 4°. In addition, we also investigated the performance of two categorical observer CMFs (i.e., S2 in Sarkar's model and B17 in BIGC model). In comparison to the four CIE standard CMFs, both the S2 and B17 CMFs had better performance, with the B17 CMFs resulting in smaller average color differences. For the individual primary sets, the S2 CMFs had the best performance when the blue or green primary, or both of blue and green primaries, was shifted (i.e., L3, L4, and L5 primary sets), while the B17 CMFs had the best performance when the blue or green primary was shifted with the red primary (i.e., L6 and L7 primary sets).

The serious problem caused by the shift of the blue primary (i.e., peak wavelength from 452 to 472 nm) generally corroborated Thornton's prime color theory (i.e., from the prime color region to the anti-prime color region). This, together with the variation of the performance of the CMFs, clearly suggested that different CMFs would be needed for characterizing or calibrating color matches using different primary sets, which does not completely support the assumption that CMFs can be directly derived through a linear transformation of cone fundamentals. Therefore, a deeper understanding about the color matching mechanism of the human visual system is truly needed, especially the primaries with narrower primaries will be more and more common.

Funding. Beijing Municipal youth talent support program; College's Scientific Research Project (BIGC Ec202003, BIGC Ec202102); Research Grants Council, University Grants Committee (PolyU 152063/18E).

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Disclosures. The authors declare no conflicts of interest.

Data Availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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