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RESEARCH ARTICLE

Effect of observer age and stimulus size on the color matching performance

Yuetong Shen[1,2] | Min Huang[1] | Xinyuan Gao[1] | Minchen Wei[2,3] | Xuping Gong[1] | Dan Wang[1]

[1]Printing and Packaging Engineering, Beijing Institute of Graphic Communication, Beijing, China

[2]Color, Imaging, and Illumination Laboratory, The Hong Kong Polytechnic University, Kowloon, Hong Kong

[3]Color Imaging and Metaverse Research Center, The Hong Kong Polytechnic University, Kowloon, Hong Kong

Correspondence
Min Huang, Printing and Packaging Engineering, Beijing Institute of Graphic Communication, Beijing, China.
Email: huangmin@bigc.edu.cn

Minchen Wei, Color Imaging and Metaverse Research Center, The Hong Kong Polytechnic University, Kowloon, Hong Kong.
Email: minchen.wei@polyu.edu.hk

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Abstract

The performance of color matching functions (CMFs) is important to color specification and calibration. In comparison to the great number of studies focusing on the effect of primary set, few studies focused on how observer age and field of view (FOV) jointly affected the performance of CMFs. In this study, a color matching experiment with three different primary sets, which were carefully selected based on our previous study, was carried out by two observer age groups under four FOVs (i.e., 2°, 4°, 8°, and 13°). The results suggested that the observer age had a more significant effect than the FOV, and the change of the FOV did not introduce a systematic trend to the color matching results. Neither the CIE 1931 2° nor 1964 10° CMFs were found to accurately characterize the color matches. The CIE 2006 CMFs with the FOV set to the experiment setup also did not have good performance. On average, the CIE 2006 2° CMFs were found to have the best performance, without considering the effects of the observer age and FOV.

KEYWORDS

color matching functions, display calibration

1 | INTRODUCTION

Color matching functions (CMFs) play a critical role in color specifications and calibrations for a wide range of applications. The CIE 1931 2° CMFs are the most widely used in practice, which is also included in various standards and guidelines.[1] Stimuli having the same tristimulus values (i.e., chromaticity coordinates and luminance), which are derived using the spectral power distributions (SPDs) and CMFs, are believed to produce the same perceived color appearance. A great number of works have found that stimuli with the same chromaticities had mismatched color appearance, which has led to the investigations on the factors affecting the performance of CMFs. Primary set, field of view (FOV), and observer age have been identified as the important factors. In particular, the CIE 1964 10° CMFs were proposed to characterize the change of FOV from 2° to 10°, and the CIE 2006 CMFs were proposed to characterize the change of FOV from 1° to 10°, and the observer age from 20 to 60.[1–3]

Most recent work mainly focused on how different primary sets affected the performance of the CMFs, finding that the performance significantly varied with the primary sets.[4–6] Meanwhile, several studies focused on how FOV affected the performance of the CIE CMFs. For example, Hu and Houser[7] performed the investigations with a fixed primary set but two different FOVs (i.e., 10° vs. 102° × 50°). Wu and Wei[8,9] carried out a color matching experiment using different primary sets at two FOVs (i.e., 4.77° vs. 20.2°). In Huang et al.,[10] human observers evaluated the color differences between metameric stimuli pairs with FOVs of 2.9° and 8.6°. All of these found the significant effect of FOV. Li et al. carried out a color matching experiment using different primary sets to produce test stimuli and a halogen lamp with a filter to produce a reference stimulus, with the bipartite field of 2°, 4°, 6°, 8°, and 10°. It was found that the optimal field size estimated using the CIE 2006 CMFs was close to half the actual size.[11] In contrast, the number of studies focusing on the effect of observer age is even less. Huang et al.[12] investigated the differences between young (19 to 25 years) and senior (60 to 75 years) observers at an FOV of 11.4°, and also three age groups (i.e., young: 19 to 27 years, middle-aged: 37 to 45 years, and senior: 63 to 83 years) at an FOV of 8.2° using different primary sets. In Li et al., though age was not found to be a significant factor, its interaction with primary set was a significant factor.[6] The effect of the observer age was expected, due to the change of the macular pigment, spectral optical density, and peak optical density.

Given the significance of both observer age and FOV, our recent work[13] specifically investigated how FOV (i.e., 2.9° vs. 8.6°) and observer age (young: 21 to 25 years; senior: 60 to 86 years) jointly affected the performance of the CMFs through color difference evaluations. This study was carefully designed to further investigate how four different FOVs (i.e., 2°, 4°, 8°, and 13°) affected the color matching performed by the young and senior observers using different primary sets. In particular, we are interested to find whether there exists a CMF set for characterizing the color matches with these four FOVs for the different primary sets and observer ages.

2 | METHODS

2.1 | Apparatus and setup

The reference stimulus was produced by an iPad Pro 2021, which contained three primaries (i.e., red, green, and blue). The test stimuli were produced by a six-channel spectrally tunable LED device containing two sets of red, green, and blue primaries (i.e., R1 and R2, G1 and G2, and B1 and B2). Figure 1 shows the relative SPDs of the primaries, with the colorimetric characteristics listed in Table 1.

The primaries of the LED device were organized into three primary sets (i.e., L1, L2, and L3), which had the same red primary (i.e., R1) but different blue and green primaries (i.e., L1: R1-G2-B1; L2: R1-G1-B1; L3: R1-G2-B2). This was mainly because past work has shown that the shift of the red primary wavelength caused little impact. Thus, we purposely included large shifts to the blue and green primaries in this study. Table 2 summarizes the wavelength shifts of the L1, L2, and L3 in comparison to the iPad Pro, with Figure 2 showing the color gamut calculated using the CIE 1931 2° CMFs.

The iPad Pro had a light emitting area of 24.7 cm × 17.8 cm; the LED device had a light emitting area of 29.0 cm × 22.4 cm. Four sets of black frames with different sizes of square openings were used to cover the light emitting areas, as illustrated in Figure 3, and the observer was seated 50 cm away, creating four FOVs of 2°, 4°, 8°, and 13°.

The uniformity and stability of the LED device and the iPad were confirmed through a series of measurements. In particular, the uniformity was verified by measuring the chromaticity difference between the center and the four corners, with the center calibrated to the D50 chromaticities. The mean chromaticity differences were 0.0006 and 0.0005 $u'_{10}v'_{10}$ units for the LED device and the iPad respectively. The stability was verified by measuring the chromaticity shifts in 120 min with an interval of 5 min. The mean chromaticity differences were 0.0017 and 0.002 $u'_{10}v'_{10}$ units for the LED device and the iPad, respectively. Thus, the devices were believed to produce reliable results.

The iPad was calibrated to produce a D65 reference stimulus, with the measured chromaticities of (0.3133, 0.3276) using the CIE 1931 2° CMFs and luminance of 87 cd/m^2. For the LED device, a remote-control panel can be used to adjust the intensity of each primary from 0% to 100% with a step of 0.1%. The chromaticities of the reference stimulus were also calculated using the 12 sets of CMFs described in the analyses, and the mean chromaticity difference from the mean $\Delta u'v'$ was 0.0025 units.

2.2 | Observer

A total of 88 observers, including 58 young (24 males and 34 females) and 30 senior (11 males and 19 females). The young observers aged between 19 and 25 years (mean = 20, SD = 1.48) and the senior observers aged

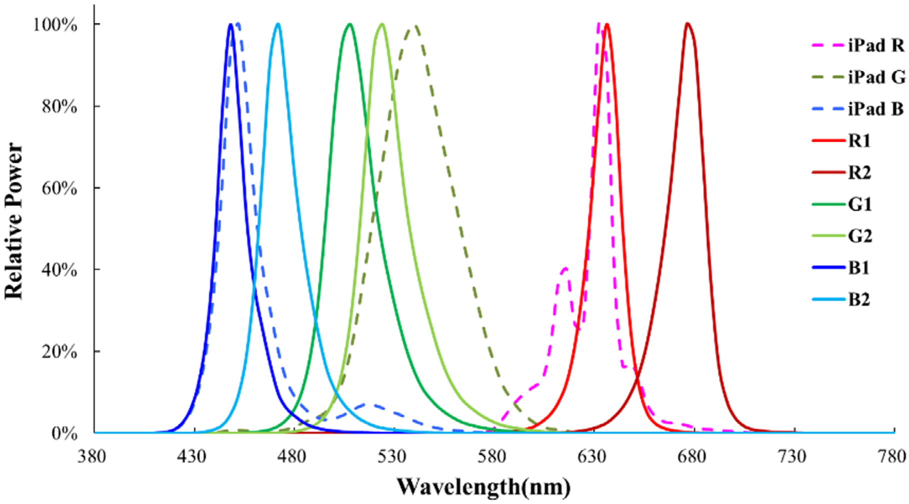

FIGURE 1 Relative spectral power distributions of the primaries used in the iPad Pro and the LED device.

TABLE 1 Summary of the colorimetric characteristics of the primaries, with the CIE 1964 10° color matching functions (CMFs) used for calculations.

Primaries		λ_{max}/nm	FWHM/nm	x_{10}	y_{10}	u'_{10}	v'_{10}
iPad Pro	R	632	28	0.644	0.335	0.449	0.526
	G	540	46	0.339	0.572	0.148	0.561
	B	452	22	0.145	0.083	0.157	0.201
LED device	R1	636	16	0.693	0.307	0.524	0.521
	R2	676	24	0.715	0.285	0.573	0.514
	G1	508	26	0.118	0.707	0.042	0.566
	G2	524	28	0.223	0.730	0.079	0.581
	B1	448	16	0.149	0.044	0.184	0.122
	B2	472	20	0.107	0.160	0.091	0.306

TABLE 2 Summary of the primary set, together with the differences of the peak wavelengths and FWHM. The color gamut areas were calculated using the CIE 1931 2° color matching functions (CMFs).

	Δλmax/nm			ΔFWHM/nm			
Primaries	ΔR	ΔG	ΔB	ΔR	ΔG	ΔB	Color gamut area
iPad Pro (R, G, B)	-	-	-	-	-	-	0.1491
L1 (R1, G2, B1)	4	−16	−4	−12	−18	−6	0.1984
L2 (R1, G1, B1)	4	−32	−4	−12	−20	−6	0.1878
L3 (R1, G2, B2)	4	−16	20	−12	−18	−2	0.1869

between 62 and 87 years (mean = 71, SD = 5.7). All the observers had normal color vision, as tested using the Ishihara Color Vision Test.

2.3 | Experimental procedures

Upon arrival, the observer was required to provide personal information and to complete the Ishihara Color Vision Test. Then he or she moved to the experimental area, with the general illumination in the space switched off. After two minutes of dark adaptation, the LED device and the iPad, which had been switched on for 30 min for warm-up, with one of the four frames placed were presented to the observer, with the observer seated 50 cm away and at the center point between the two. The experimenter explained the task (i.e., to match the color appearance of the test stimulus to that of the reference stimulus by adjusting the intensities of the three channels) and how to use the remote-control panel. Then the observer performed two matches to get familiar with the control panel, after which the main experiment began. For each adjustment, the observer was free to take as much time as he or she needed, with the chromaticities of the test stimulus started from the D50 chromaticities. Once he or she was satisfied with the match, a

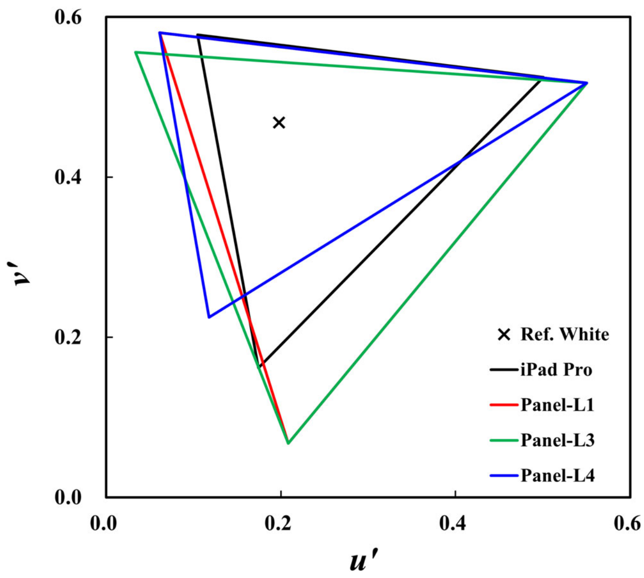

FIGURE 2 Color gamuts of the primary sets used in this experiment, were calculated using the CIE 1931 2° color matching functions (CMFs).

PhotoResearch PR-655 spectroradiometer was used to measure the SPD of the stimuli. After that, the primary set of the test stimulus was switched to another. After completing three matches for one FOV, the frame set was replaced by another set, with the order of the four completely randomized. For characterizing the intra-observer variations, a repeated match was performed for two of the four FOVs using the L1 primary set. Thus, each observer completed 14 matches in total.

3 | RESULTS

3.1 | Intra- and inter-observer variations

The intra- and inter-observer variations were characterized using the mean color difference from the mean (MCDM) in the CIE 1976 $u'_{10}v'_{10}$ chromaticity diagram. In particular, the intra-observer variations were characterized based on the color difference between the two sets of the repeated adjustments made by each observer; the inter-observer variations were characterized based on the color differences between all 14 adjustments made by each observer and the average of the 14 adjustments made by all the observers (i.e., an average observer). Table 3 summarizes the maximal, minimal, and mean of the MCDM values, with all the values similar to those in the recent work. In general, the intra-observer variations were smaller than 0.004, which is ~1 JND (note: 0.004 is for the CIE 1931 2° CMFs). In addition, it can be found that both the intra- and inter-observer variations were larger for the senior observers. Also, a smaller FOV led to a larger inter-observer variation, which was consistent with that of Li et al.[11,14]

3.2 | Observer metamerism (OM)

The inter-observer variations, in terms of MCDM values in $u'_{10}v'_{10}$ units, for the different primary sets and FOVs, as summarized in Figure 4, also suggested the observer metamerism. It can be found that the observer metamerism was less serious for the young observers. Among the three primary sets, the observer metamerism was the least serious for the L1 set, which was likely due to the similar wavelengths between the L1 and reference primary sets and was consistent to our past work. For the L2 and L3 sets, the OM introduced by the former was more serious to the senior observers, while the OM introduced by the latter was more serious to the young observers. Such a trend held for all the FOVs. The best performance of the L1 set and the worst performance of the L2 set corroborated the findings of Li et al., though the reference stimuli in the two experiments were not the same.[13]

3.3 | Performance of the CMFs for characterizing the average results

The chromaticities of the reference stimulus and the stimuli adjusted by the observers were calculated using 12 different CIE CMFs, including the CIE 1931 2°, 1964 10°, and the CIE 2006 CMFs with FOVs varying from 1° to 10° with a step of 1°, with the age set to 20 and 70 for the two age groups respectively. Table 4 summarizes the average chromaticity difference $\Delta u'v'$. It can be observed that both CIE 1931 and 1964 CMFs had better performance for characterizing the color matches made by the young observers, while the performance of the CIE 2006 CMFs varied with the FOVs. On average, the CIE 2006 2° CMFs had the best performance for both the young and senior observers.

Despite the consistent results of the CMFs having the best performance, the performance of the CMFs can be observed to vary with the primaries. In particular, the L1 primary set always had the smallest $\Delta u'v'$ values for both the young and senior observers, regardless of the CMFs used. For the other two primary set, the L2 set always had the smaller $\Delta u'v'$ values for the young observers, while the L3 set always had the smaller values for the senior observers. This suggested that the 32 nm shift of the green primary in the L2 set introduced a serious effect to the senior observers, while the 20 nm shift of the

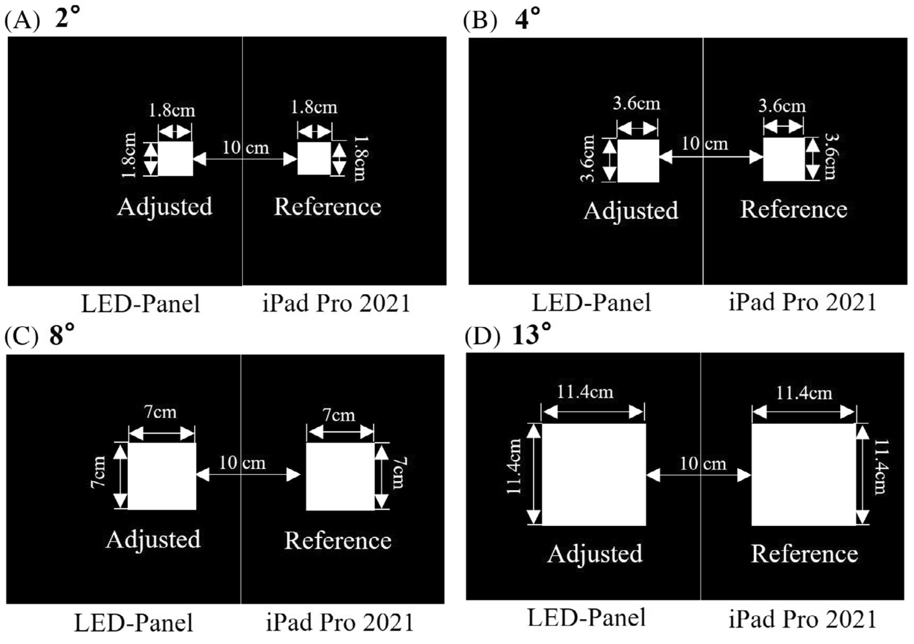

FIGURE 3 Illustration of the four field of views (FOVs) created using four sets of black frames.

TABLE 3 Summary of the intra- and inter-observer variations, in terms of the mean color difference from the mean in the CIE 1976 $u'_{10}v'_{10}$ chromaticity diagram.

		FOVs	2°	4°	8°	13°
Senior	Intra-observer	Max	0.0044	0.0038	0.0055	0.0031
		Min	0.0003	0.0003	0.0009	0.0001
		Mean	0.0023	0.0016	0.0026	0.0012
	Inter-observer	Max	0.0102	0.0078	0.0096	0.0086
		Min	0.0009	0.0008	0.0004	0.0003
		Mean	0.0044	0.0038	0.0043	0.0028
Young	Intra-observer	Max	0.0024	0.0017	0.0019	0.0030
		Min	0.0001	0.0001	0.0001	0.0000
		Mean	0.0007	0.0007	0.0008	0.0012
	Inter-observer	Max	0.0047	0.0048	0.0034	0.0039
		Min	0.0006	0.0002	0.0002	0.0001
		Mean	0.0020	0.0019	0.0016	0.0019

blue primary in the L3 set introduced a serious effect to the young observers. This was likely due to the higher optical density of the crystalline lens for the senior observers, making them become less sensitive to radiation at shorter wavelengths.

3.4 | Effect of FOV on the performance of CMFs

The analyses were further performed on each FOV individually, with the average $\Delta u'v'$ values for each of the 12 CMFs shown in Figure 5. It can be observed that the CMFs with the FOVs set to the size used in the experiment never had the best performance. The CIE 2006 1°, 2°, 3°, and 4° CMFs had the best performance when the FOV was set to 2°, 4°, 8°, and 13°, respectively, which seemed to be similar to the finding in Li et al. that the best performance for the CIE 2006 CMFs was found when the FOV was set to about half of the actual FOV used in the experiment.[11] The performance of the CIE 2006 2° was least affected by the actual FOV used in the experiment, while the CMFs with the FOV set to a larger FOV (e.g., 10°) had larger variations with the actual FOV used in the experiment. In other words, it would be better to set the FOV size to 2° for the CIE 2006 CMFs, which generally had the best and stable performance regardless of the actual CMFs used in the experiment.

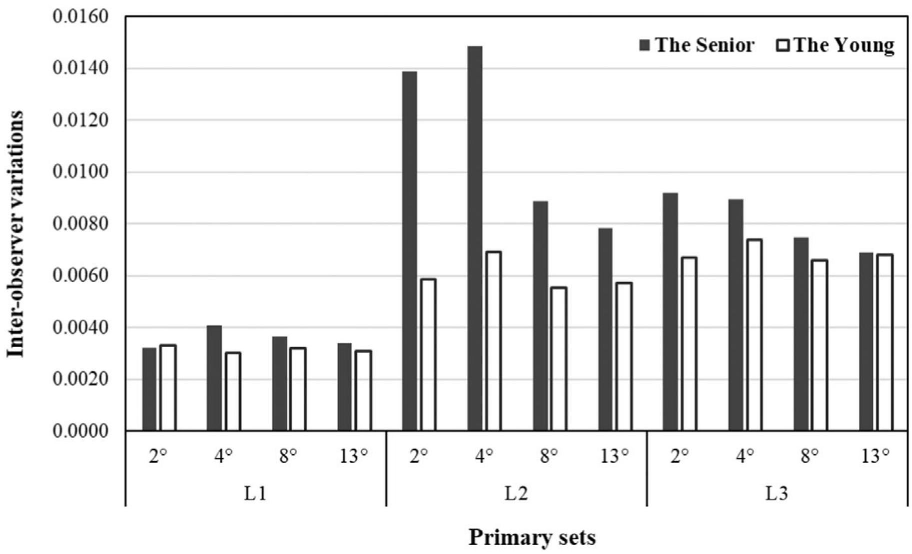

FIGURE 4 Summary of the inter-observer variations for the different primary sets with the different field of views (FOVs).

TABLE 4 Summary of the average chromaticity differences between the reference stimulus and the stimuli adjusted by the observers using the 12 CIE color matching functions (CMFs), with the CMFs having the best performance (i.e., the smallest $\Delta u'v'$ value) underlined.

CMFs		L1 Young	L1 Senior	L2 Young	L2 Senior	L3 Young	L3 Senior	Mean Young	Mean Senior
CIE1931		0.0038	0.0069	0.0119	0.0197	0.0209	0.0170	0.0122	0.0145
CIE 1964		0.0056	0.0103	0.0133	0.0355	0.0140	0.0332	0.0110	0.0263
CIE2006	1°	0.0062	0.0072	0.0149	0.0132	0.0166	0.0096	0.0126	0.0100
	2°	0.0036	0.0039	0.0093	0.0108	0.0104	0.0081	0.0078	0.0076
	3°	0.0046	0.0036	0.0092	0.0112	0.0096	0.0087	0.0078	0.0078
	4°	0.0055	0.0040	0.0105	0.0121	0.0106	0.0096	0.0089	0.0086
	5°	0.0060	0.0042	0.0119	0.0130	0.0120	0.0105	0.0100	0.0093
	6°	0.0063	0.0045	0.0133	0.0139	0.0136	0.0113	0.0111	0.0099
	7°	0.0065	0.0046	0.0145	0.0146	0.0151	0.0119	0.0120	0.0104
	8°	0.0066	0.0047	0.0155	0.0152	0.0165	0.0125	0.0129	0.0108
	9°	0.0067	0.0047	0.0164	0.0157	0.0177	0.0129	0.0136	0.0111
	10°	0.0067	0.0048	0.0173	0.0161	0.0189	0.0134	0.0143	0.0115
Mean		0.0057	0.0053	0.0132	0.0159	0.0147	0.0132	0.0112	0.0115

3.5 | Shift of the chromaticities

Figure 6 shows the average chromaticities of the stimuli adjusted by the observers with each primary set, labeled with different colors, and each FOV size, labeled with different shapes, in the a^*-b^* plane in the CIELAB color space using the CIE 1964 10° CMFs. The adjusted stimuli generally shifted toward the $-a^*$ direction for the young observers, corresponding to a green tint. In contrast, the chromaticities were further shifted toward the $+b^*$ direction for the senior observers, corresponding to a yellow tint. This corroborates the finding that the neutral stimuli always appear pinkish or greenish to observers with different ages. The differences between the two age groups were the most obvious for the L3 primary set with the shift of the blue primary, which can be explained by the greater differences in the short-wavelength region between the CMFs of the two age groups. The shifts of the chromaticities with the

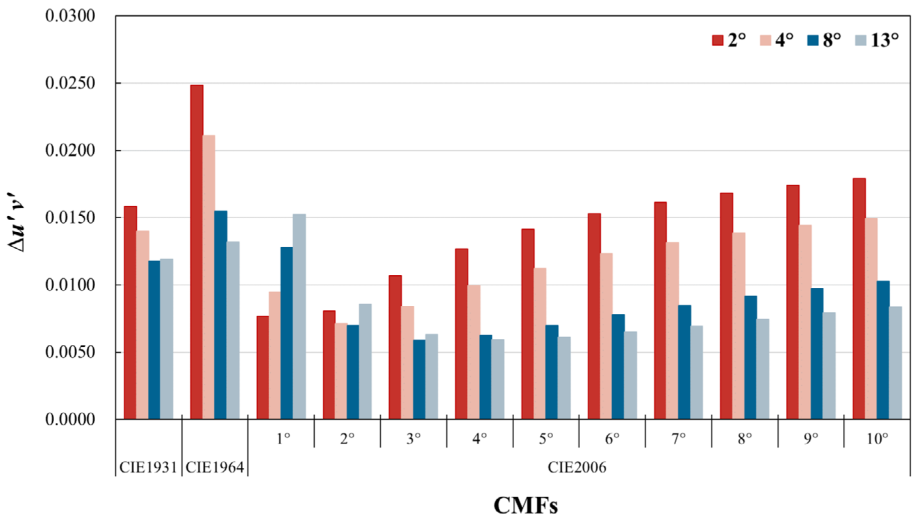

FIGURE 5 Summary of the average chromaticity differences between the reference stimulus and the stimuli adjusted by the observers using the 12 CIE color matching functions (CMFs) for each field of view (FOV) used in the experiment.

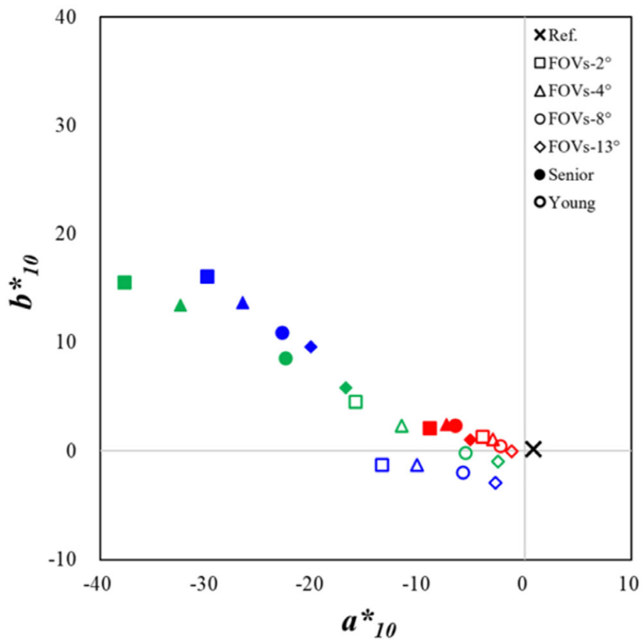

FIGURE 6 Average chromaticities of the stimuli adjusted by the observers, with the different primary sets (L1: Red; L2: Green; L3: Blue) and different field of views (FOVs), for the young and senior observers in the a^*-b^* plane of the CIELAB color space, with the chromaticities calculated using the CIE 1964 10° color matching functions (CMFs).

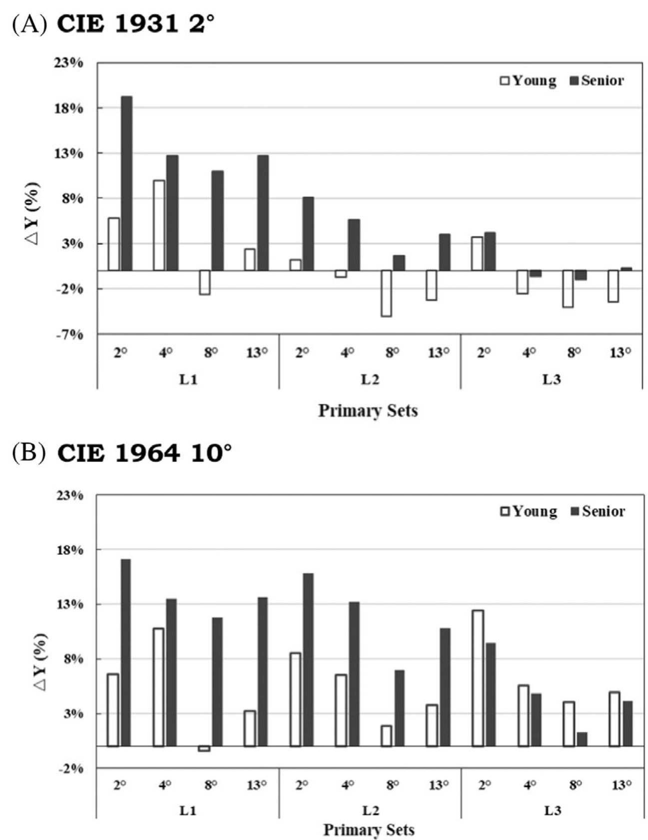

FIGURE 7 Average luminance differences of the stimuli adjusted by the observers in comparison to the reference stimulus using the CIE 1931 2° and CIE 1964 10° color matching functions (CMFs). (A) the CIE 1931 2° CMFs; (B) the CIE 1964 10° CMFs.

different FOVs were consistent regardless of the primary sets and observer ages, with a larger FOV shifting the chromaticities toward the $+a^*-b^*$ direction, corresponding to a pinkish tint. This was also consistent to the simulation results in Reference 15 in which senior observers with the CMFs simulated using the individual colorimetric models were found to perceive a pinkish tint if two displays were calibrated using the CIE 10° CMFs.

3.6 | Luminance adjusted by the observers

Last but not least, the observers were able to adjust the intensities of the primaries in this experiment. This allowed the change of the luminance, together with the chromaticities, which was different from the other recent studies in which the luminance of the stimulus was fixed. When the reference and test stimuli were matched in appearance, it was expected that the luminance should also be the same. Figure 7 shows the average luminance differences of the stimuli adjusted by the observers using the CIE 1931 2° and CIE 1964 10° and CMFs, which can be as large as around 20%, especially for the senior observers. On average, the luminance difference was much larger for the senior observers. Interestingly, the L1 primary set had the largest luminance difference, though it had the smallest chromaticity difference. For the L2 and L3 sets, the former had smaller luminance differences for the young observers, while the latter had smaller luminance differences for the senior observers. Such a relationship is also applied to the chromaticity differences, as described in Section 3.3.

For the CIE 1931 2° CMFs, the luminance differences were generally the smallest when the FOV was 2°; for the CIE 1964 10° CMFs, the luminance differences were generally the smallest when the FOV was 8°. This suggested that both CMFs were able to characterize the perceived brightness when the FOV matched to how the CMFs were designed.

4 | CONCLUSION

A color matching experiment was carried out, with two age groups of observers using three primary sets to match the color appearance of a white reference stimulus under four FOVs (i.e., 2°, 4°, 8°, and 13°). As expected, the different primary sets had significant impacts on the performance of the CIE CMFs. Moreover, the observer age was found to have a more significant effect than the FOV, with the stimuli adjusted by the senior observers tended to appear greenish. None of the CIE 1931 2°, 1964 10°, and the 2006 CMFs with the FOV set to the experiment setup was able to accurately characterize the color matches. On average, the CIE 2006 CMFs with the FOVs set to 2° were found to have the best performance, if the effects of primary set and observer ages were not considered.

AUTHOR CONTRIBUTIONS

Yuetong Shen: data collection, data analysis, draft preparation. **Min Huang:** conceptualization, manuscript revision. **Xinyuan Gao:** data collection, data analysis. **Minchen Wei:** conceptualization, manuscript revision. **Xuping Gong:** data collection. **Dan Wang:** data collection.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

ORCID

Yuetong Shen https://orcid.org/0009-0007-0761-0185
Minchen Wei https://orcid.org/0000-0002-0045-3160

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AUTHOR BIOGRAPHIES

Yuetong Shen is a PhD student at the Hong Kong Polytechnic University. He received his BSc degree at Beijing Institute of Graphic Communication. His research mainly focuses on color appearance and color matching functions.

Min Huang is a professor at Beijing Institute of Graphic Communication. She received her PhD degree in the National Lab of Color Science and Engineering from Beijing Institute of Technology. She has undertaken some projects related to color difference evaluation, observer metamerism, and categorical color matching functions.

Xinyuan Gao is a MS student at Beijing Institute of Graphic Communication. She received her bachelor degrees from North University of China. Her research mainly focuses on cross-media color reproduction.

Minchen Wei is a professor at the Hong Kong Polytechnic University. He received his PhD degree at the Pennsylvania State University. Currently, he is a vice president of CIE. His research mainly focuses on color science and imaging science.

Xuping Gong is a MS student at Beijing Institute of Graphic Communication. He received his bachelor degrees from Qufu Normal University of China. His research mainly focuses on color quality evaluation.

Dan Wang is a MS student at Beijing Institute of Graphic Communication. She received her bachelor degrees from Qufu Normal University of China. Her research mainly focuses on performance of color matching functions.

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