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Effect of display size on color matching performance

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Abstract: The performance of color matching functions (CMFs) is important for color specification and calibration, especially for modern displays. The interaction between size and primary was seldom investigated. In this study, four groups of color matching experiments were carried out, which included a wide range of stimulus sizes and primary sets. The results suggested that the size of stimulus played a critical role in color matching, especially when the stimuli were produced by displays having different wavelengths for the green and blue primaries. For easy applications, the stimulus sizes can be classified into three categories based on the field of view (FOV)—small (FOV < 4°), medium (FOV between 4° and 10°), and large (FOV > 10°), and the Asano2(2°), CIE 2006 4°, and Asano7(10°) recommended for the three categories respectively.

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1. Introduction

Color matching functions (CMFs) play a critical role in color specifications and calibrations for a wide range of applications. Specifically, commercial color management software often uses the CIE 1931 2° CMFs for color characterization across displays with different primary sets, which is also incorporated into various industrial standards and guidelines [1]. With the popularity of wide color gamut displays, the failure of CIE 1931 2° CMFs in color matching characterization is becoming non-trivial, especially for the color calibration on wide-screen devices with different Fields of View (FOV) [2,3]. In 1964, the CIE recommended the CIE 1964 10° CMFs for the stimuli with an FOV beyond 4° [4]. In 2006, CIE Technical Committee TC1-36 recommended a model for estimating the cone fundamentals of normal human observers with an FOV ranging from 1° to 10° [5] and later derived the corresponding CMFs and chromaticity diagrams in 2015 [6]. The development of the CIE 2006 CMFs was primarily motivated by the metameric failure associated with the previous CMFs that stimuli having the same tristimulus values or chromaticities have different color appearance.

Most recent work mainly focused on how different primary sets affected the performance of CMFs, suggesting that the performance varies significantly with the primaries [7–10]. Meanwhile, several color matching experiments were carried out using different primary sets to investigate the interaction of FOVs. For example, four different FOVs were included in Shen et al [11] (i.e., 2°, 4°, 8°, and 13°) and also in Wang et al [12] (i.e., 2.9°, 5.7°, 8.6°, and 11°), and two FOVs (i.e., 4.77° and 20.2°) were included in Wu and Wei [13]. These studies generally found that the CIE 2006 CMFs with a 2° FOV had the best performance when considering the effect of different primary sets. Li et al [14] carried out a color matching experiment using different primary sets to produce test stimuli, with the reference stimulus produced by a halogen lamp with a filter,

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and included five FOVs (i.e., 2°, 4°, 6°, 8°, and 10°). It was found that setting the FOV to half of the actual FOV used in the experiment led to the best performance if the CIE 2006 CMFs were used. It can be found that the FOVs used in these experiments were typically around 10°. Moreover, the previous studies only evaluated the CMFs recommended by the CIE. Therefore, it is worthwhile to carefully investigate whether the CIE 2006 2° CMFs are applicable to larger FOVs and whether they still offer the best performance.

This study was carefully designed to further investigate how different FOVs affect color matching performance among a large group of young, color-normal observers using various primary sets. In particular, we aimed to find the most appropriate CMFs for characterizing color matches across different FOVs on modern displays with various primaries, in terms of the full width at half maxima (FWHM) and peak wavelength.

2. Methods

2.1. Displays

We carefully selected twelve displays to carry out color matching experiments. These displays can be classified into three categories, including five professional displays (i.e., No. 1 to 5 for NEC PA242W, EIZO CG19, EIZO CG243, QUATO 220ex, and NEC PA241W), 57 consumer electronic devices (i.e., No. 6 for Huawei Mate 30, No. 7 for iPad Pro 2021, and No. 8 for 55 individual smartphones), and four LED panels (i.e., No. 9 to 12) with different spectral compositions of the RGB primaries. Figure 1 shows the spectral power distributions (SPDs) of the primaries in each group, as measured by a Photo Research PR-670 spectroradiometer. The displays with the FWHM of the primary spectra less than 20 nm were considered as narrow-band, while those with the FWHM of the primary spectra greater than 20 nm were considered as broadband. These displays were used in the four groups of color matching experiments (i.e., G.1 to G.4).

The white luminance of all displays was adjusted to 83cd/m^2–93cd/m^2 to ensure consistent and stable matching performance. For smartphones, they were used as the reference in the color matching experiment with eye protection mode, night mode, and automatic brightness disabled. Under these conditions, the measured correlated color temperatures ranged from 5000 K and 7000 K, and observers were able to achieve satisfactory color matches within this luminance range. Table 1 summarizes the colorimetric characteristics of each primary of the different displays used in the experiments. The uniformity of the displays was characterized by the chromaticity differences between the center and the four corners with the center calibrated to the D50 chromaticities, with the average chromaticity difference of 0.0013 $u'_{10}v'_{10}$ units, suggesting the high reliability of the displays.

2.2. Experiment setups

The reference and the matched displays having different spectral characteristics were placed side by side in the experiments. Different sizes of black frames were used to cover the displays for producing stimuli with different sizes, as illustrated in Fig. 2. In addition, the distance between the displays and the observers were also adjusted during the experiment, so that the FOVs of the stimuli were corresponding changed. The field of view (FOV) was defined as the angular size of the square-shaped stimulus, calculated based on the physical size of the matched stimulus and the viewing distance. In G.1 and G.4, the reference and matched stimuli had different sizes, while in G.2 and G.3, the reference and matched stimuli had the same sizes. Table 2 lists the details of the experiment setups.

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Table 1. Summary of the colorimetric characteristics of the primaries of the displays used in the four color matching experiment (i.e., G.1 to G.4), in terms of the peak wavelengths (λ_{max}), full width half maxima (FWHM), and the differences between the reference and matched displays

Experiment Group		Displays (No.)		λmax/nm			*D*λmax/nm			FWHM/nm			D FWHM/nm		
				R	G	B	R	G	B	R	G	B	R	G	B
	G.1-1	Ref.	6	628	528	464	32	-12	-28	36	24	20	16	24	16
		Mat.	3	660	516	436				52	48	36			
	G.1-2	Ref.	6	628	528	464	24	-8	-20	36	24	20	52	8	4
		Mat.	1	652	520	444				88	32	24			
G.1	G.1-3	Ref.	7	632	540	452	28	-24	-16	24	48	20	28	0	16
		Mat.	3	660	516	436				52	48	36			
	G.1-4	Ref.	7	632	540	452	20	-20	-8	24	48	20	64	-16	4
		Mat.	1	652	520	444				88	32	24			
	G.2-1	Ref.	9	636	524	448	40	0	0	16	28	16	8	0	0
		Mat.	10	676	524	448				24	28	16			
G.2	G.2-2	Ref.	9	636	524	448	0	0	24	16	28	16	0	0	4
		Mat.	12	636	524	472				16	28	20			
	G.3-1	Ref.	2	612	544	436	8	-28	0	16	11	50	-4	33	-7
		Mat.	4	620	516	436				12	44	43			
G.3	G.3-2	Ref.	2	612	544	436	48	-28	0	16	11	50	33	29	-21
		Mat.	5	660	516	436				49	40	29			
	G.3-3	Ref.	1	652	520	444	-32	-4	-8	88	32	24	-76	12	19
		Mat.	4	620	516	436				12	44	43			
	G.4-1	Ref.	8	625	533	460	11	-9	-12	29	33	18	-13	-5	-2
		Mat.	9	636	524	448				16	28	16			
	G.4-2	Ref.	8	625	533	460	51	-9	-12	29	33	18	-9	-5	-2
		Mat.	10	676	524	448				24	28	16			
G.4	G.4-3	Ref.	8	625	533	460	11	-25	-12	29	33	18	-13	0	-2
		Mat.	11	636	508	448				16	26	16			
	G.4-4	Ref.	8	625	533	460	11	-9	12	29	33	18	-13	-5	2
		Mat.	12	636	524	472				16	28	20			

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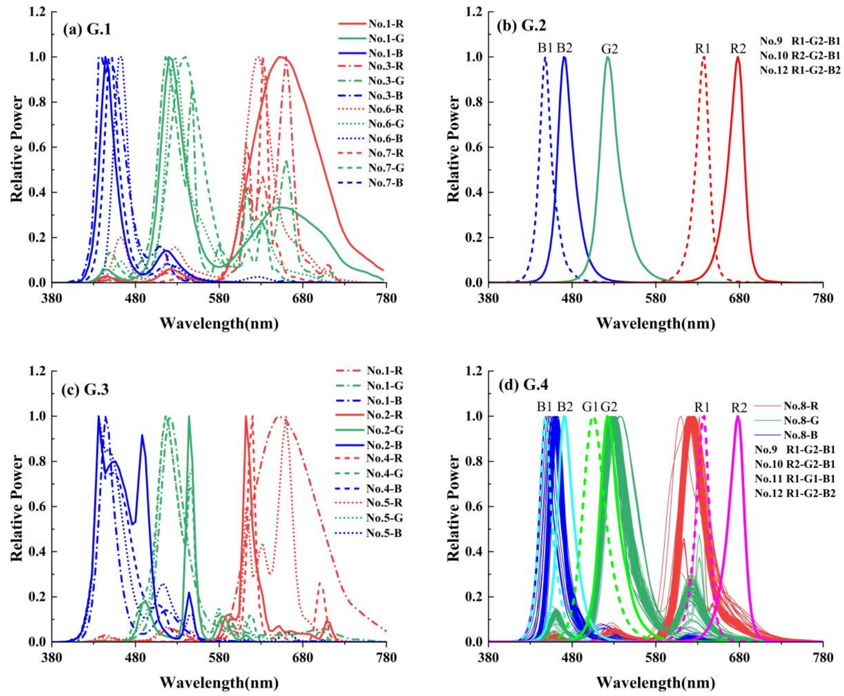

Fig. 1. Spectral power distributions of the displays used in the four color matching experiments (i.e., G.1 to G.4). (a) G.1; (b) G.2; (c) G.3; (d) G.4.

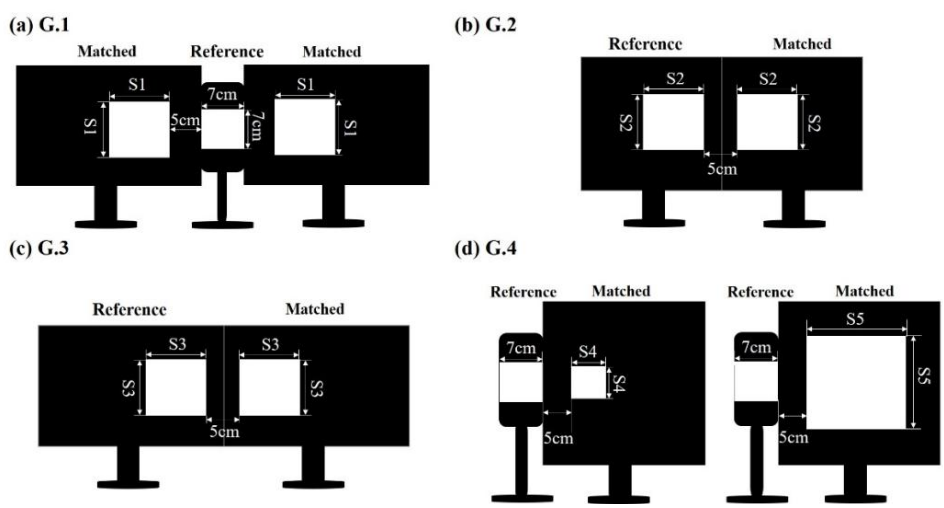

Fig. 2. Illustration of the experiment setups in the two experiments, with the numerical values summarized in Table 2. (a) G.1; (b) G.2; (c) G.3; (d) G.4.

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Table 2. Summary of the experiment setups used in the four experiments

Exp. Group	Window Size (cm)		Viewing Distance (cm)	FOVs	Exp. Group	Window Size (cm)		Viewing Distance (cm)	FOVs
G.1	S1×S1	4 × 4	50	4°	G.4	S4×S4	2.5 × 2.5	70	2°
		7 × 7		8°			4.2 × 4.2	60	4°
		20 × 20		22°			6.3 × 6.3		6°
G.2	S2×S2	3.5 × 3.5	70	2.9°			7 × 7	50	8°
		4 × 4	40	5.7°		S5×S5	8.8 × 8.8	50	10°
		4.5 × 4.5	30	8.6°			11 × 11		12.6°
		4.8 × 4.8	25	11°			14 × 14		16°
G.3	S3×S3	1.74 × 1.74	50	2°			17 × 17		19.3°
		3.5 × 3.5		4°			16 × 16	40	24°
		8.54 × 8.54		10°			20 × 20		28°
		19.44 × 19.44		22°			23 × 23		32°

2.3. Color stimuli and observers

Table 3 summarizes the information about the color stimuli, observers, and displays included in each experiment group. The reference stimuli, including a white and various colors recommended by the CIE, were produced using the reference displays, and the observers performed the color matches by adjusting the stimuli produced by the matched displays.

In G.1, 30 observers performed the matches for the red and blue stimuli once and 10 observers performed the matches for the white stimulus three times; in G.2, 35 observers performed the matches once and 10 observers performed the matches twice; in G.3, all the observers performed the matches once; in G.4, 11 observers performed the matches for three color matches twice using the four primary sets, 33 observers performed the matches using the L1 and L3 primary sets once, and the remaining 33 observers performed the matches using the L2 and L4 primary sets once.

2.4. Experiment procedure

Upon arrival, the observer was required to complete the Ishihara Color Vision Test, and the experimenter explained the task to the observer. After two minutes of dark adaptation, the observer performed two trials of match to get familiar with the control panel, then the formal experiment started. The order of the matches was randomized among the observers, and the displays were switched on 20 minutes before the experiment for stability. All the observers were students from the Beijing Institute of Graphic Communication, and had normal color vision as tested using the Ishihara Color Vision Test.

After each observer completed the experiment, the SPDs of the stimuli were measured from the observer's eye position using the spectroradiometer, which were then used for the following analyses.

Table 3. Summary of the color stimuli and observers of the four color matching experiments

Exp. Group		Display No.		FOVs	Colors	Number of Observers	Ages of Observer	No. of observations
G.1 [15]	G.1-1	Ref	6	4°, 8°, 22°	White, Red, Blue	40 (22 M and 18 F)	21~26 (mean = 22)	1080
		Mat	3					
	G.1-2	Ref	6					
		Mat	1					
	G.1-3	Ref	7					
		Mat	3					
	G.1-4	Ref	7					
		Mat	1					
G.2 [12]	G.2-1	Ref	9	2.9°, 5.7°, 8.6°, 11.0°	White, Red, Blue	45 (21 M and 24 F)	19~26 (mean = 21)	1320
		Mat	10					
	G.2-2	Ref	9					
		Mat	12					
G.3 [16]	G.3-1	Ref	2	2°, 4°, 10°, 22°	White, Grey, Red, Blue, Green, Yellow	63 (19M and 44F)	18~25 (mean = 20)	1512
		Mat	4					
	G.3-2	Ref	2					
		Mat	5					
	G.3-3	Ref	1					
		Mat	4					
G.4	G.4-1	Ref	8	2°, 4°, 6°, 8°, 10°, 12.6°, 16°, 19.3°, 24°, 28°, 32°	White	77 (48M and 29F)	21~26 (mean = 23)	2904
		Mat	9					
	G.4-2	Ref	8					
		Mat	10					
	G.4-3	Ref	8					
		Mat	11					
	G.4-4	Ref	8					
		Mat	12					

3. Results and discussions

3.1. Observer variations

The observer variations were characterized using the chromaticity difference $\Delta u'_{10}v'_{10}$ calculated using the CIE 1964 10° CMFs. In particular, the intra-observer variations were characterized using the chromaticity difference $\Delta u'_{10}v'_{10}$ between the two repeated matches made 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 observer and the average chromaticities of the stimuli adjusted by all the observations (i.e., an average observer). Table 4 summarizes the minimum, maximum, and mean values of these variations for each experiment.

It can be observed that the average inter-observer variations were generally greater than the average intra-observer variations, regardless of the primary sets. And the variations were generally comparable to those in several recent color matching experiments [7,8,9], suggesting the reliability of the experiment.

Table 4. Intra- and inter-observer variations characterized using the $\Delta u'_{10}v'_{10}$ values for the four experiments

Variations		G.1	G.2	G.3	G.4
Intra-observers	Min	0.0002	0.0002	\	0.0003
	Max	0.0079	0.0140	\	0.0057
	Mean	0.0028	0.0040	\	0.0020
Inter-observers	Min	0.0006	0.0004	0.0015	0.0007
	Max	0.0110	0.0299	0.0287	0.0163
	Mean	0.0042	0.0078	0.0054	0.0052

3.2. Performance of the CMFs for characterizing the average results

The chromaticities of the reference stimuli and the stimuli adjusted by the observers were calculated using 42 different CMFs, including 12 CIE recommended CMFs (i.e., the CIE 1931 2°, CIE1964 10°, and the CIE 2006 CMFs with the FOV ranging from 1° to 10° with a step of 1° and the age set to the observers' average age). In addition, several categorical CMFs were also included, such as Sarkar 1 to Sarkar 8 (FOV = 10°), Asano 1 to Asano 10 (FOVs = 2° and 10°), BIGC 17 [17] developed based on printed samples with an FOV of 10°, and Ko M-LMS [18] developed for modern displays with FOVs of 2°, 4°, 15°, and 26°.

Table 5 summarizes the $\Delta u'v'$ values between the reference and matched stimuli for those with the FOV smaller and greater than 4°. The smaller the value, the better the performance of the CMFs. The three smallest values for each experiment group are highlighted with a shaded background, with the smallest value underlined. When the FOVs were smaller than 4°, Asano 2 (2°) and the CIE 2006 3° had the best performance, with the average $\Delta u'v'$ of 0.0043 and 0.0045. In contrast, when the FOVs were greater than 4°, the CIE 2006 4° and 5° CMFs were the best, with the average $\Delta u'v'$ of 0.0042. All of these values were around the threshold of JNCD [19]. Based on these results, 12 sets were selected from the 42 CMFs for further analyses, including the CIE 2006 CMFs ranging from 2° to 10° (with a step of 1°), and Asano 2 (2°), Asano 9 (2°), Asano 7 (10°). It should be noted that all participants in this study were young adults (18–26 years old). Age-related changes in ocular media and cone sensitivity may influence CMF performance, thus, the present findings and recommendations are most applicable to younger populations.

3.3. Parametric effects on color matching results

3.3.1. Effect of primary set

The results of the white stimuli were used to analyze the effect of the primary set. Figure 3 shows the average $\Delta u'v'$ calculated using the 12 selected CMFs for each experiment. It can be observed that all the values in G.1 and G.3 were below 0.0060, since the professional displays had broadband spectra. In G.1-2, G.1-4, G.2-1 and G.4-1, the peak wavelengths of the matched displays were 652-520-444 nm (No.1), 676-524-448 nm (No.10), and 636-524-448 nm (No.9), resulting in small values, which was consistent to those from the previous studies [8,10,13]. This was likely due to the fact that the peak wavelengths were similar to those used in Stiles and Burch (i.e., 645.2-526.3-444.4 nm) [20] with a shift smaller than 10 nm.

Moreover, the different CMFs resulted in the largest variations in G.1-3, G.2-2, G.3-1, G.3-2, G.4-3, and G.4-4, suggesting that the shifts of the green and blue primaries mattered a lot. For example, the shift of blue primary towards the shorter or longer wavelength (i.e., G.4-1 and G.4-4) introduced significant differences to the performance of the various CMFs. Also, the results suggested that the primaries used in Stiles and Burch generally introduced little difference to the different CMFs.

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Table 5. Performances of 42 CMFs for characterizing the color matches, in terms of the $\Delta u'v'$ values, when the stimuli had FOVs smaller than 4° and greater than 4°.

CMFs	Small FOVs (≤4°)					Large FOVs (>4°)				
	G.1	G.2	G.3	G.4	Mean	G.1	G.2	G.3	G.4	Mean
CIE1931 2°	0.0060	0.0096	0.0046	0.0089	0.0073	0.0070	0.0118	0.0049	0.0137	0.0093
CIE1964 10°	0.0052	0.0094	0.0039	0.0091	0.0069	0.0049	0.0073	0.0036	0.0051	0.0052
CIE 2006 1°	0.0055	0.0073	0.0072	0.0093	0.0073	0.0063	0.0089	0.0076	0.0151	0.0095
2°	0.0030	0.0063	0.0040	0.0053	0.0046	0.0037	0.0067	0.0043	0.0089	0.0059
3°	**0.0027**	0.0066	**0.0035**	0.0053	0.0045	**0.0029**	0.0059	0.0034	0.0062	0.0046
4°	0.0031	0.0072	0.0035	0.0061	0.0050	0.0029	**0.0057**	**0.0033**	0.0049	0.0042
5°	0.0035	0.0080	0.0037	0.0070	0.0055	0.0032	0.0059	0.0034	0.0043	**0.0042**
6°	0.0038	0.0087	0.0038	0.0077	0.0060	0.0034	0.0063	0.0036	0.0041	0.0043
7°	0.0041	0.0093	0.0040	0.0083	0.0064	0.0037	0.0067	0.0037	0.0041	0.0045
8°	0.0044	0.0098	0.0041	0.0088	0.0068	0.0039	0.0072	0.0038	0.0042	0.0048
9°	0.0046	0.0103	0.0042	0.0093	0.0071	0.0041	0.0076	0.0039	0.0044	0.0050
10°	0.0048	0.0107	0.0043	0.0097	0.0074	0.0043	0.0080	0.0040	0.0047	0.0052
Asano 1(2°)	0.0042	0.0073	0.0049	0.0067	0.0058	0.0050	0.0089	0.0053	0.0116	0.0077
2	0.0031	**0.0059**	0.0035	**0.0048**	**0.0043**	0.0035	0.0063	0.0037	0.0080	0.0054
3	0.0086	0.0118	0.0079	0.0123	0.0101	0.0097	0.0143	0.0083	0.0182	0.0126
4	0.0037	0.0082	0.0043	0.0071	0.0058	0.0038	0.0064	0.0044	0.0059	0.0051
5	0.0060	0.0095	0.0066	0.0109	0.0082	0.0069	0.0128	0.0070	0.0176	0.0111
6	0.0054	0.0080	0.0055	0.0077	0.0067	0.0060	0.0079	0.0058	0.0100	0.0074
7	0.0049	0.0060	0.0043	0.0062	0.0054	0.0054	0.0080	0.0048	0.0116	0.0074
8	0.0077	0.0119	0.0076	0.0125	0.0099	0.0088	0.0152	0.0081	0.0192	0.0128
9	0.0028	0.0064	0.0040	0.0054	0.0046	0.0033	0.0062	0.0040	0.0078	0.0053
10	0.0124	0.0159	0.0105	0.0170	0.0139	0.0136	0.0188	0.0109	0.0234	0.0167
Asano 1(10°)	0.0052	0.0091	0.0040	0.0092	0.0069	0.0049	0.0068	0.0038	0.0050	0.0051
2	0.0046	0.0108	0.0045	0.0096	0.0074	0.0039	0.0081	0.0042	0.0046	0.0052
3	0.0083	0.0089	0.0049	0.0102	0.0081	0.0084	0.0088	0.0051	0.0098	0.0080
4	0.0057	0.0118	0.0045	0.0110	0.0082	0.0052	0.0090	0.0042	0.0058	0.0061
5	0.0049	0.0090	0.0043	0.0089	0.0068	0.0046	0.0069	0.0041	0.0057	0.0053
6	0.0067	0.0102	0.0042	0.0107	0.0080	0.0064	0.0079	0.0040	0.0061	0.0061
7	0.0037	0.0099	0.0038	0.0082	0.0064	0.0032	0.0073	0.0034	**0.0039**	0.0045
8	0.0069	0.0080	0.0042	0.0090	0.0070	0.0070	0.0078	0.0043	0.0084	0.0069
9	0.0049	0.0107	0.0046	0.0101	0.0076	0.0043	0.0080	0.0042	0.0049	0.0054
10	0.0110	0.0112	0.0061	0.0123	0.0102	0.0115	0.0125	0.0065	0.0146	0.0113
Sarkar1	0.0119	0.0171	0.0068	0.0170	0.0132	0.0119	0.0163	0.0070	0.0152	0.0126
S2	0.0042	0.0065	0.0038	0.0075	0.0055	0.0041	0.0065	0.0038	0.0057	0.0050
S3	0.0062	0.0075	0.0038	0.0100	0.0069	0.0061	0.0068	0.0039	0.0071	0.0060
S4	0.0057	0.0095	0.0045	0.0108	0.0076	0.0053	0.0074	0.0043	0.0063	0.0058
S5	0.0044	0.0086	0.0044	0.0091	0.0066	0.0040	0.0065	0.0041	0.0051	0.0049
S6	0.0040	0.0114	0.0055	0.0105	0.0078	0.0038	0.0091	0.0053	0.0070	0.0063
S7	0.0058	0.0106	0.0061	0.0106	0.0083	0.0060	0.0106	0.0062	0.0108	0.0084
S8	0.0061	0.0099	0.0057	0.0110	0.0082	0.0061	0.0092	0.0058	0.0094	0.0076
BIGC17	0.0042	0.0078	0.0050	0.0116	0.0071	0.0040	0.0058	0.0048	0.0139	0.0071
Ko M LMS	0.0044	0.0098	0.0046	0.0080	0.0067	0.0042	0.0074	0.0041	0.0056	0.0053

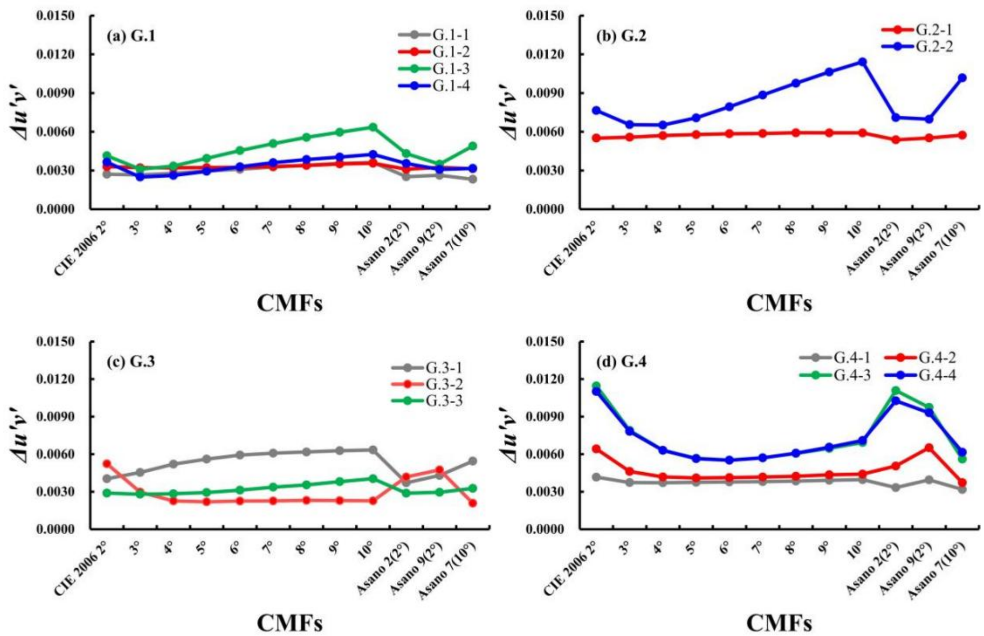

Fig. 3. Average Δ*u'v'* values calculated using the 12 selected CMFs for the white stimuli in each experiment. (a) G.1; (b) G.2; (c) G.3; (d) G.4.

3.3.2. Effect of FOV

Figure 4 shows the average Δ*u*'*v*' of each FOV in each experiment group. It can be observed that the different FOVs had little effect in G.1 and G.3, which was likely due to the broadband spectra used in these displays (i.e., No.1 to 5). In contrast, when displays with narrowband spectra were used in G.2 and G.4, the effect of FOV became obvious, especially when the FOVs were smaller than 4°.

The results of G.4 were further analyzed, since there were 11 FOVs in G.4. Table 6 summarizes the results calculated using the 12 CMFs. Asano2(2°) had the best performance for an FOV between 1° and 4°. When the FOV was greater than 10°, Asano7(10°) had the best performance. For the CIE 2006 CMFs, it can be observed that setting the FOVs to the size used in the experiment did not have the best performance. However, when the FOV was set to half of that used in the experiment with the FOV smaller than 10°, the CIE 2006 CMFs had relatively better performance, which was consistent to the results in several past studies. When the FOV was greater than 10°, the performance of the various CMFs became stable.

We then reanalyzed the results by classifying the FOVs into three categories—small (FOV smaller than 4°), medium (FOV between 4° and 10°), and large (FOV greater than 10°), with the average Δ*u*'*v*' summarized in Table 7 and Fig. 5. It can be observed that the performance of different CMFs varied significantly for the small FOVs, but was relatively stable for the large FOVs. And the results suggested that Asano2(2°) should be used for the small FOV, Asano7(10°) should be used for the large FOV, and the CIE 2006 4° should be used for the FOVs between 4° and 10°.

3.4. Color difference thresholds of different FOVs

Based on the results presented above, Figs. 6, 7, and 8 show the Δ*u*'*v*', Δ*E**ab, and ΔE_{00} values calculated using Asano2(2°) and Asano7(10°) for the different FOVs. It can be observed that the

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Table 6. Summary of $\Delta u'v'$ calculated using the 12 CMFs for each FOV used in G.4

CMFs	2°	4°	6°	8°	10°	12.6°	16°	19.3°	24°	28°	32°
CIE1931 2°	0.0080	0.0099	0.0115	0.0121	0.0128	0.0136	0.0139	0.0144	0.0146	0.0156	0.0152
CIE1964 10°	0.0102	0.0080	0.0062	0.0057	0.0055	0.0050	0.0048	0.0050	0.0047	0.0048	0.0047
CIE 2006 2°	0.0051	0.0055	0.0068	0.0073	0.0079	0.0089	0.0093	0.0095	0.0099	0.0104	0.0105
3°	0.0061	0.0044	0.0046	0.0049	0.0052	0.0061	0.0064	0.0066	0.0070	0.0074	0.0075
4°	0.0073	0.0049	0.0040	0.0041	0.0041	0.0047	0.0049	0.0052	0.0055	0.0058	0.0059
5°	0.0082	0.0057	0.0042	0.0040	0.0039	0.0040	0.0041	0.0043	0.0045	0.0048	0.0049
6°	0.0090	0.0064	0.0047	0.0043	0.0040	0.0038	0.0038	0.0039	0.0039	0.0042	0.0042
7°	0.0097	0.0070	0.0052	0.0046	0.0043	0.0039	0.0038	0.0037	0.0036	0.0039	0.0038
8°	0.0102	0.0075	0.0057	0.0051	0.0046	0.0040	0.0039	0.0038	0.0036	0.0038	0.0036
9°	0.0106	0.0079	0.0061	0.0055	0.0050	0.0043	0.0041	0.0040	0.0037	0.0038	0.0036
10°	0.0110	0.0084	0.0065	0.0059	0.0054	0.0045	0.0043	0.0042	0.0038	0.0039	0.0037
Asano2(2°)	0.0049	0.0046	0.0059	0.0064	0.0069	0.0080	0.0084	0.0086	0.0090	0.0095	0.0096
Asano9(2°)	0.0058	0.0050	0.0057	0.0062	0.0068	0.0077	0.0082	0.0084	0.0088	0.0093	0.0094
Asano7(10°)	0.0095	0.0069	0.0052	0.0046	0.0042	0.0037	0.0036	0.0034	0.0032	0.0036	0.0033

Table 7. Summary of $\Delta u'v'$ calculated using the 12 CMFs for the three FOV categories in each experiment

CMFs	G.1			G.2			G.3			G.4		
	Small	Medium	Large	Small	Medium	Large	Small	Medium	Large	Small	Medium	Large
CIE1931 2°	0.0060	0.0069	0.0070	0.0096	0.0116	0.0122	0.0046	0.0047	0.0051	0.0089	0.0121	0.0146
CIE1964 10°	0.0052	0.0049	0.0049	0.0094	0.0074	0.0072	0.0039	0.0031	0.0041	0.0091	0.0058	0.0048
CIE 2006 2°	0.0030	0.0036	0.0037	0.0063	0.0065	0.0067	0.0040	0.0039	0.0047	0.0053	0.0073	0.0098
3°	0.0027	0.0030	0.00288	0.0066	0.00575	0.0059	0.00348	0.0030	0.0039	0.0053	0.0049	0.0068
4°	0.0031	0.0030	0.00285	0.0072	0.00568	0.0057	0.00352	0.0029	0.0038	0.0061	0.0041	0.0053
5°	0.0035	0.0032	0.0031	0.0080	0.0059	0.0058	0.0037	0.0030	0.0039	0.0070	0.0040	0.0044
6°	0.0038	0.0035	0.0034	0.0087	0.0063	0.0062	0.0038	0.0031	0.0040	0.0077	0.0043	0.0040
7°	0.0041	0.0037	0.0036	0.0093	0.0068	0.0065	0.0040	0.0033	0.0042	0.0084	0.0047	0.0038
8°	0.0044	0.0039	0.0039	0.0098	0.0072	0.0070	0.0041	0.0034	0.0043	0.0089	0.0051	0.0038
9°	0.0046	0.0041	0.0041	0.0103	0.0077	0.0074	0.0042	0.0034	0.0043	0.0093	0.0055	0.0039
10°	0.0048	0.0042	0.0043	0.0107	0.0081	0.0078	0.0043	0.0035	0.0044	0.0097	0.0059	0.0041
Asano2(2°)	0.0031	0.0036	0.0035	0.0059	0.0061	0.0064	0.00353	0.0033	0.0040	0.0048	0.0064	0.0089
Asano9(2°)	0.0028	0.0032	0.0033	0.0064	0.0060	0.0062	0.0040	0.0036	0.0045	0.0054	0.0062	0.0086
Asano7(10°)	0.0037	0.0032	0.0032	0.0099	0.0074	0.0071	0.0038	0.0030	0.0039	0.0082	0.0047	0.0035

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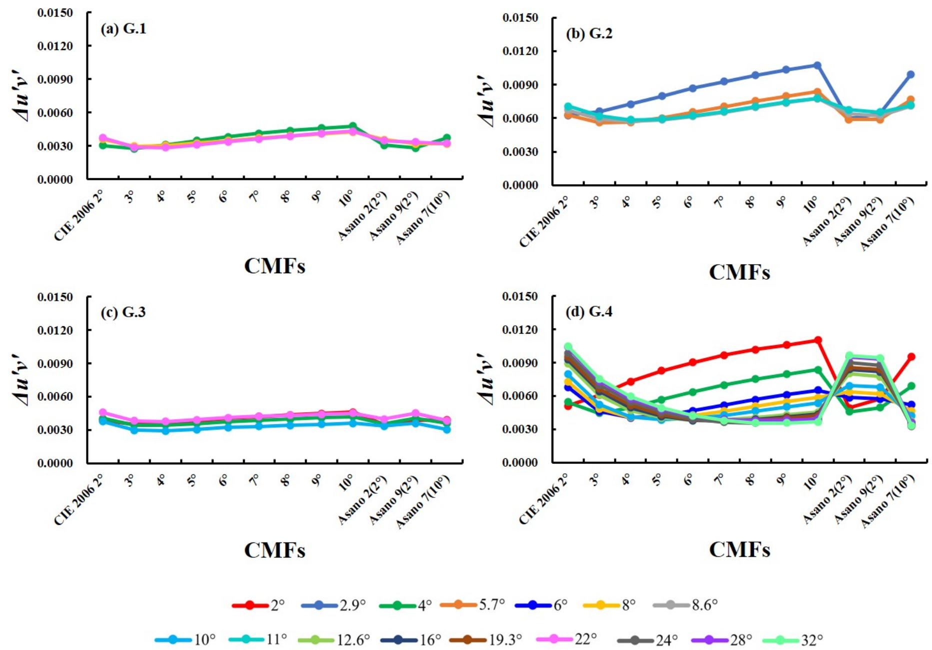

Fig. 4. Average Δ*u'v'* values of the white stimulus calculated using the 12 selected CMFs in each experiment. (a) G.1; (b) G.2; (c) G.3; (d) G.4.

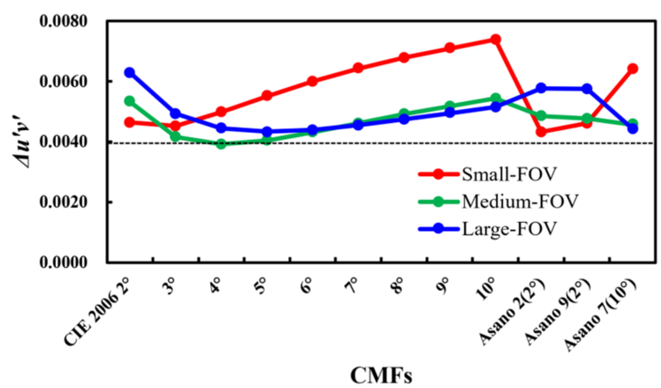

Fig. 5. Average Δ*u'v'* calculated using the 12 CMFs for the three FOV categories in the experiments.

values were relatively constant in G.4-1 and G.4-2. In contrast, the results from G.4-3 and G.4-4 produced variations with the changes of FOVs. These values can be considered as the threshold for producing a just-noticeable-color difference. In order to model the relationship between the threshold and the FOV, a power function, as described in Eq. (1), was used.

$$\triangle E_{JNCD} = \frac{\Delta E}{a \times FOV^{b} + c} \tag{1}$$

where ΔE_{JNCD} is the threshold, ΔE is the original value of Δ*u'v'*, ΔE^*_{ab}, and ΔE_{00}, *a*, *b*, and *c* are the parameters, which were optimized by minimizing the differences from the predicted values and the experiment results. Table 8 lists the values of these parameters, and Fig. 9 shows

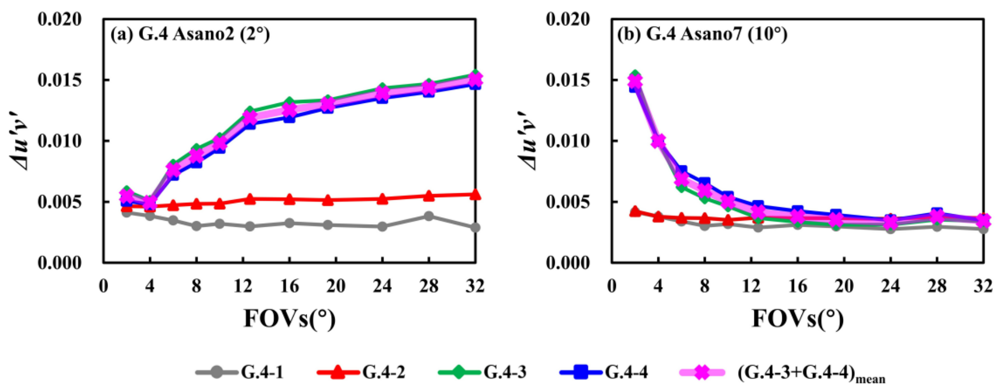

Fig. 6. $\Delta u'v'$ calculated using Asano2(2°) and Asano7(10°) for the different FOVs in G.4 experiment. (a) Asano2(2°); (b) Asano7(10°).

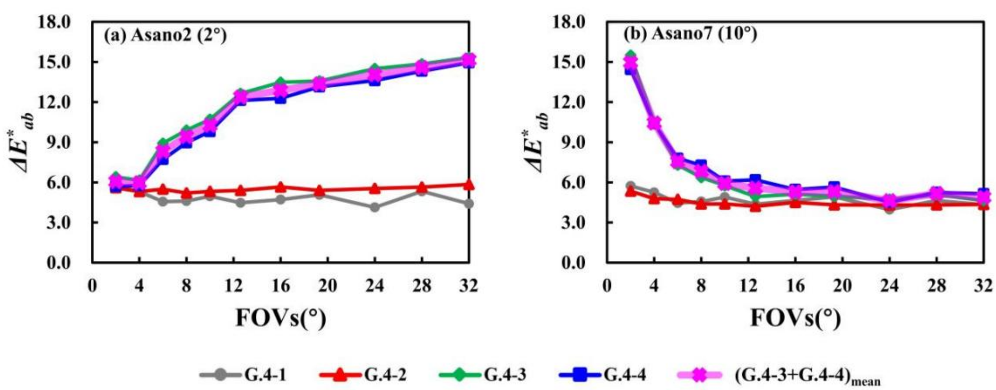

Fig. 7. ΔE^*_{ab} calculated using Asano2(2°) and Asano7(10°) for the different FOVs in G.4 experiment. (a) Asano2(2°); (b) Asano7(10°).

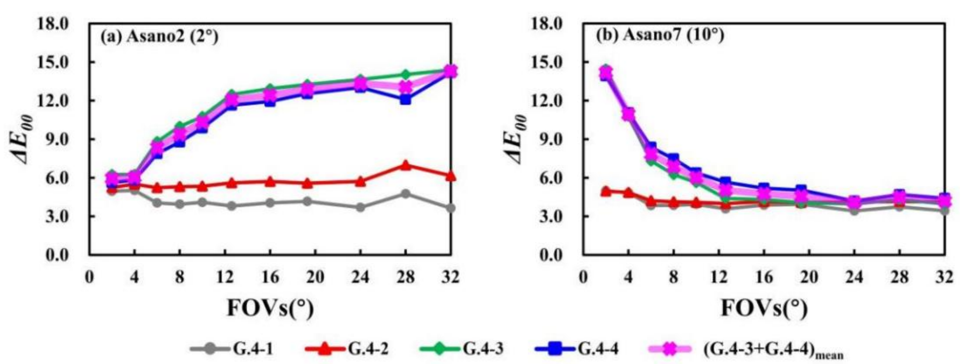

Fig. 8. ΔE_{00} calculated using Asano2(2°) and Asano7(10°) for the different FOVs in G.4 experiment. (a) Asano2(2°); (b) Asano7(10°).

the predicted values and the experiment results. Equation (1) is particularly useful when the ratio between two different FOVs is greater than 3 (e.g., an FOV of 2° versus 15°), which generally introduces pronounced observer metamerism. The closer the ΔE_{JNCD} value to 1, the higher the

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accuracy of the prediction. For color management in practice, such an approach allows accurate estimations and characterizations for different FOVs.

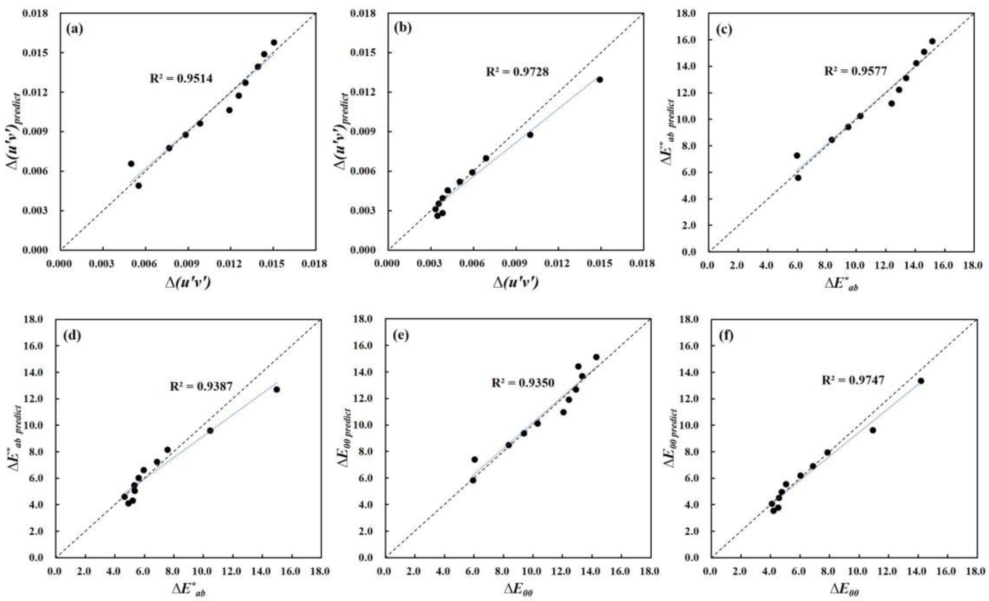

Fig. 9. Comparisons between predicted color difference and experiment results. (a) $\Delta u'v'$ by Asano2(2°); (b) $\Delta u'v'$ by Asano7(10°); (c) ΔE^*_{ab} by Asano2(2°); (d) ΔE_{ab} by Asano7(10°); (e) ΔE_{00} by Asano2(2°); (f) ΔE_{00} by Asano7(10°).

Table 8. Summary of the coefficients of a, b, and c used in Eq. (1) for optimizing the calculated threshold and the experiment results

[!b]

CMFs		*a*	*b*	*c*
	$\Delta u'v'$	0.0035	0.4315	0.000195
Asano 2(2°)	ΔE_{00}	4.4365	0.3500	0.1978
	ΔE^*_{ab}	4.2555	0.3794	0.0680
	$\Delta u'v'$	0.0194	-0.5480	-0.000292
Asano 7(10°)	ΔE_{00}	18.7050	-0.4670	-0.1580
	ΔE^*_{ab}	16.9940	-0.3990	-0.1590

4. Conclusions

This study was designed to carefully investigate the interaction between stimulus size characterized using FOV and primary set on color matching performance. Thirteen groups of color matching experiments were carried out. The effects of primary set and stimulus size were found as expected. When the two stimuli had different primaries in blue and green, the effect of the stimulus size was much obvious. For practical applications, it was recommended to classify the stimulus size into three categories—small (FOV < 4°), medium (FOV between 4° and 10°), and large (FOV > 10°), and the Asano2(2°), CIE 2006 4°, and Asano7(10°) recommended for the three categories respectively. In addition, a formula was proposed to derive the just-noticeable-color-difference for different FOVs. Since the participants in this study were young adults (18-26 years), elder observers may exhibit different visual perceptions. This represents a limitation of the present work, and future studies should extend to aged populations to refine CMF recommendations.

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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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