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An Experiment to Evaluate Observer Metamerism on Displays

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Abstract

This article describes two color matching experiments using 6 displays and a visual trichromator based on spectral tunable LED technology respectively. Ten observers performed the experiment. The results were used to reveal observer metamerism between displays, to derive each individual's color matching functions (CMFs), and to test their performance against the available CMFs. Comparing different CMFs to estimate observer metamerism of displays, individual CMF (expressed by mean ΔE_{00} *of 2.7) clearly outperformed the others. Amongst the CIE CMFs, CIE 2006 10° performed the best (5.1), followed by the other color matching functions, CIE 1931 2° gave the worst performance (11.1). The results indicates a large error could occur by adopting the current standard (CIE 1931 2°) to specify colors and this can be much improved using the individual CMFs. A simulation analysis of display primaries was also conducted to show peak wavelength to have a greater impact on observer metamerism than peak bandwidth.*

Introduction

An important goal of color science is to achieve precise color reproduction across different media, including real-world objects and displays, in a way that faithfully reflects the spectral information in the image. Light stimuli from different objects enter the human eye and activates its three types of light-sensitive receptors: L-, M-, and S-cones. Objects match in colors match when they produce the same responses in the three types of cones. Models that define the human eye's response to spectral stimuli are called color matching functions (CMFs), and they include the fundamental CMFs or cone spectral sensitivities. The industry commonly uses standard observer functions that are supposed to represent average responses. However, because of individual variations, these averages work less well for observers whose CMFs are differ from the mean functions. This leads to observer metamerism (OM), where different spectral distributions may produce the same color perception for one observer but not for another. In many cases, OM is less pronounced because natural environmental spectral power distributions (SPDs) are broadband, and so the variations in responses caused by different CMFs are relatively small. However, in some cases, particularly with display technologies that use narrow bandwidth lights to produce wider color gamuts the failures of OM can be large [1]. Therefore, several studies focused on measuring and reducing observer metamerism. As early as the 1980s, the CIE recognized that differences between observers could lead to failures in color reproduction and proposed a standard deviate observer (SDO) [2] using four deviation functions to express these differences. However, it was later noted that this index underestimated the variability between observers [3]. Moreover, the SDO model was never adopted or used by the industry. In 2006, the International Commission on Illumination (CIE) Technical Committee TC 1-36 approved Stockman and Sharpe's [4] estimates of cone spectral sensitivities as a "physiologically relevant" standard for color vision and published CIEPO06 [5]. Based on the 1959 Stiles and Burch [6] dataset, CIEPO06 provides a practical method of defining mean cone fundamentals for fields of view from 1° to 10° field of view for ages of aged 20 to 80 years. The CIEPO06 cone fundamentals can be linearly transformed into XYZ CMFs as outlined in CIEPO15. In 2010, To assess individual variability in color matches, Sarkar et al. [7] proposed the concept of seven categorical observers based on cluster analysis of the Stiles & Burch dataset and simulated data using the CIEPO06 model. In 2013, Fairchild & Heckaman [8] introduced a modified physiological model considering factors influencing CMFs, validating its representativeness through Monte Carlo simulations. Asano et al. [9] improved Sarkar's setup in 2014 for a large-scale color matching experiment, using Fairchild's model [8] to generate CMFs and validate experimental results effectively. Long & Fairchild [10] subsequently proposed metamerism indices based on their CMFs and color difference models. These were used to analyze various display primaries to predict and assess metamerism levels in primary design. In 2016, Asano et al. [11] integrated physiological research findings to propose an individual CMF model based on ten parameters (age, field of view, transmittance of lens and macular, optical densities and shifts of LMS), named "Asano's model" on the foundation of CIEPO06. They assumed Gaussian distribution of these parameters to compute mean and standard deviation. Asano and Fairchild [12] expanded upon Sarkar's [7] categorical observer concept and Asano's [11] 10-parameter individual CMF model in 2020, proposing a 10-class categorical observer scheme. Huang et al. [13] introduced four observer classes based on print color matching experiments and Asano's model. Xie et al. [14] in 2020 introduced an improved inter-observer metamerism index known as POM2. Shi and Luo [15] conducted display color matching experiments involving 20 participants across five displays, using a 3x3 matrix method to correct observer metamerism. Trump et al. [16] in 2023 quantitatively evaluated the distribution of OM across the chromaticity diagram in color displays. Ko et al. [17] conducted color matching experiments with 11 combinations using seven displays, determining optimal CMFs, followed by validation experiments with an LCD and a laser projector to confirm CMFs selection.

In the earlier studies on observer metamerism, many researchers have used the method of training the Asano model with SPD color pairs to reduce observer metamerism, rather than obtaining CMFs specifically tailored to individual observers. Additionally, there could be a lack of rigorous control over geometric conditions during display experiments. In this experiment, rigid geometric control conditions were applied to the displays, along with the use of a multi-spectral trichromator (LEDMax®, a multi-channel adjustable LED device). This approach, combined with modifications based on CIEPO06 by Stockman and Rider [18], aimed to train more accurate and direct individual CMFs and investigate their performance. Furthermore, this study also explored the effects of peak wavelength and half-width on OM through simulation of display primaries.

Experimental Setup

There were two experiments in the present study. Experiment 1 was a color matching experiment based on display devices, and Experiment 2 was a color matching experiment based on a trichromator. Ten participants (8 males and 2 females, aged 21-27, with normal color vision and no eye diseases) took part in this phase of the experiment. The display experiment used a D65 white at 150 nits as the target color and white point for calculations, while the trichromator experiment used a D65 white at 100 nits. Both used CIE 2006 10° as the CMF for calculations. In each experiment session, observers first underwent about 15 minutes of training.Then proceeded to approximately 3 minutes of adaptation. After adaptation, observers were asked to use knobs and a keyboard to perform 22 times of color matching in CIELAB space, with the starting point of the match randomly generated around the target point having a color difference greater than 15 (CIEDE2000, or ΔE_{00}[19]). After a short break and repositioning, experiment 2, consisting of 10 groups, was conducted after re-adaptation. Each group experiment was repeated twice, and each participant performed a total of 32 color matches.

Experiment 1: Display Experiment

The Experiment 1 uses five different types of displays and one spectral tunable continuous light source, which we refer to as Display 1 to Display 6. The purpose is to obtain matches across the diplays under rigorously controlled view conditions that appear the same but with different spectral power distributions (SPDs) as determined by the display primaries. We built aa set up for observing two screens side-by-side (Figure 1). It as constructed using 3D printing and includes movable high-reflectance mirrors. These mirrors reflect the displays perpendicularly to the line of sight. Special slots accommodate smartphones, ensuring they maintain a perpendicular orientation to the line of sight. The distance between the observer and the observation window is controlled to fix the field of view to 10°. Rigorous light shielding prevents any stray light from interfering with the observer's matches. Each display underwent a one-hour warm up period before the experiment, during which they displayed a gray background to ensure thermal equilibrium throughout the experiment.

Table 1 lists the six display devices. The panel positions of Display 2 to Display 5 were finely adjusted and fixed to be perfectly perpendicular to the line of sight at specific mirror positions. Display 1 (laser projector) and Display 6 (spectrally tunable continuous light source) project onto the same screen, which is perpendicular to the line of sight, with both illuminating the screen obliquely (not simultaneously). Display 1 achieves uniform brightness within the viewing window (measured at four sampling points: edges and center) of over 97% through built-in geometric adjustments, while Display 6 achieves this through additional diffusers.

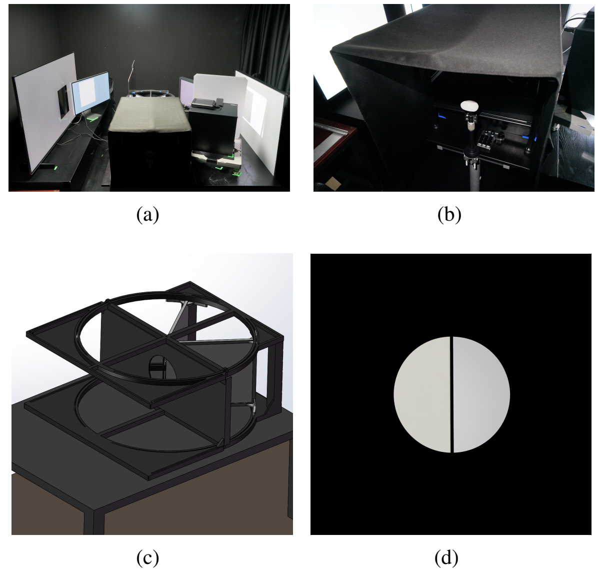


Figure 1. *(a) System overview (b)The observer operating position with a light shielding hood and equipped with cheek rest to position the head, provides a dedicated keyboard for color matching (c)View Windows, mirrors, and guides in SolidWorks files (d) Color patches from the observer's point of view, here showing display 5 (a mobile phone fixed to a slot) and display 6 (a screen illuminated by a spectral tunable continuous light source), both achieve good uniformity*

Table1: Display peak wavelength and FWHM

	Peak WL (nm)			FWHM (nm)		
Display	R	G	B	R	G	B
(1)Laser_Projector	644	527	462	6.8	11.7	4.6
(2)LCD_1	650	519	450	91.1	32.4	21.0
(3)LCD_2	631	533	447	7.9	43.1	16.9
(4)QD_miniLED	623	538	446	22.8	24.4	15.0
(5)OLED(Cellphone)	629	527	461	28.6	28.0	15.9

The target color for the experiment was set to 150 nits of D65 white, rather than the 100 nits used in Experiment 2. The adjustment is derived from integrating the brightness upper limits and control precision of different devices. Each device underwent independent color calibration using a KONICA MINOLTA CS2000A. For Displays 1 to 5, 3D-LUTs were used for color characterisation, and was tested at 20 points near the experimental target color. Non-laser displays achieved accuracy below 0.6 (ΔE_{00}), while the laser projector achieved below 1.4 (ΔE_{00}). Display 6 utilized dedicated control software to ensure that the white point accuracy was better than 1.5 (ΔE_{00}). Despite using a replication method to measure matching results, higher replication accuracy remains effective in improving the precision of color matching, as indicated by feedback from experienced participants.

The experiment was designed with a total of 11 pairs of display devices, as listed in Table 2. There was no single "reference" display set throughout the experiment because the focus of this phase was on measuring and reducing observer metamerism between displays, rather than color calibration against a "reference display."

Table2: 11 pairs of display combinations

combinations	1	2	3	4	5	6	7	8	9	10	11
Match Display	1	1	1	2	3	3	3	4	4	4	5
Ref. Display	3	4	5	5	2	5	6	2	5	6	6

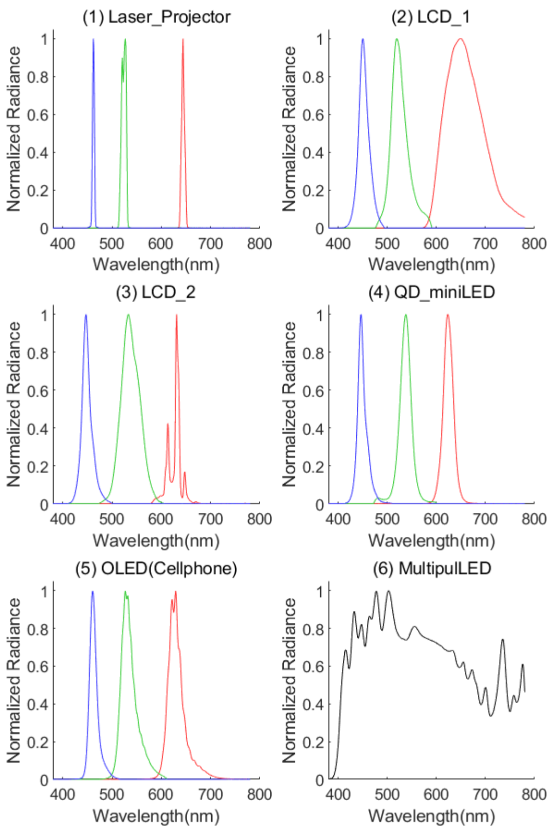
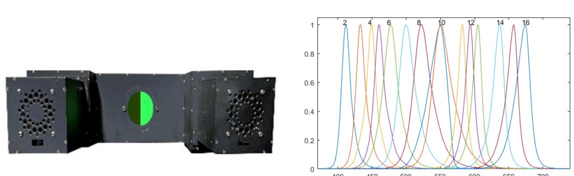


Figure 2. The SPDs of 6 displays in Experiment 1

Experiment 2: Trichromator Experiment

Experiment 2 in the second part were based the trichromator shown in Figure 3(a). This device has been described before (REFS). It was used to obtain observer matches between triplets of LEDs with different SPDs and a white standard, form which it is possible to derive individual LMS cone spectral sensitivities, and thus individual XYZ CMFs[20].



(a) (b)

Figure 3. (a)System overview (b)Normalized SPD of channel 2-16

Due to minimal inter-channel crosstalk but slight peak wavelength shifts, a simplified 3D-LUT model was applied to calibrate this device. After calibration, each set of primaries was tested with 20 points near the experimental target colors. With its 10-bit channel depth, the mean accuracy was 0.25 (ΔE_{00}). This experiment used a different set of primaries compared to previous ones, reducing the number of primary combinations from 11 groups to 5 groups, as shown in Table 3. This reduction allowed for the possibility of conducting both parts of the experiment in a single session.

Table3: Channel combinations of the experiment

	match			reference		
No.	R	G	B	R	G	B
(1)	14	10	5	12	8	3
(2)	13	8	6	14	8	4
(3)	15	7	3	16	9	5
(4)	14	9	5	12	7	4
(5)	13	8	2	11	8	3

Results

A total of 320 sets of color matches ((11+5)*2*10) were collected. The experimental results were reproduced using a fully authentic simulation method to obtain the original spectrum of matching results. After preheating, all displays were restored to their state at the time of matching completion. The SPDs were measured twice using a KONICA MINOLTA CS2000A spectroradiometer, and the average of these measurements was taken.

Observer Variation

Observers' color matching inter- and intra-observer variations were measured using intra-MCDM and inter-MCDM, respectively. Intra-MCDM represents the internal variability of an individual across two repeated experiments, while inter-MCDM quantifies the variability among 10 observers using (ΔE_{00} with CIE 2006 10° CMFs. The white point was based on the target values from each experiment (150 nit D65 and 100 nit D65), as shown in Table 4. All participants achieved better intra-MCDM data compared to inter-MCDM, particularly several proficient participants demonstrating excellent internal consistency.

Table4: Individual intra-MCDM and inter-MCDM

	Experiment 1		Experiment 2	
Observer	intra	inter	intra	inter
(1)	1.14	2.46	1.08	3.75
(2)	1.15	2.16	0.91	3.94
(3)	1.22	2.90	0.54	3.41
(4)	1.87	3.03	1.48	4.04
(5)	1.74	3.76	1.67	5.07
(6)	0.58	2.22	0.54	2.08
(7)	0.45	2.62	0.85	6.44
(8)	1.19	3.46	1.66	3.59
(9)	0.89	3.09	1.42	4.57
(10)	1.17	2.46	2.34	3.71
MEAN	1.14	2.82	1.25	4.06

CMF Compare

The fitting of CMFs to individual visual characteristics is quantified by the Observer Metamerism Magnitude (OMM)[17], represented by equation (1).

$$\mathrm{OMM} = \frac{1}{N}\sum_{i=1}^{N}\left(E_{00}(L^*a^*b^*_{\mathrm{ref},i}, L^*a^*b^*_{\mathrm{matched},i})\right) \quad (1)$$

Using the SPD data obtained from matches from Experiment 1, various average CMFs were compared. These include standard CIE observers, ten categorical observers by Asano et al.[12] (labeled as Asano_CATn), CMF7 recommended by Ko et al.[17] (labeled as Ko_CMF7). For individual observers, data from the second part of the experiment were utilized. These were optimized using genetic algorithms (GA) based on the model proposed by Stockman and Rider [18] . The complete results are presented in Table 5, with the CMFs having the lowest average OMM for each group, alongside standard observers listed in Figure 4. It is inferred that various average CMFs have an upper limit in correcting OM, whereas individual CMFs can surpass this limit.

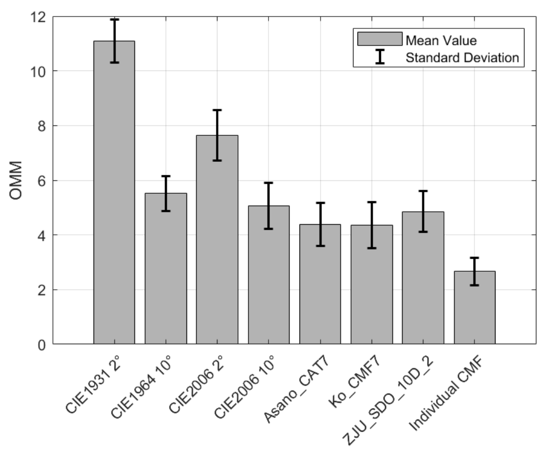


Figure 4. *The CMFs having the lowest average OMM for each group, alongside standard observers*

Display OM and simulation experiment

Different displays with different primaries cause different degrees of OM and perceptual differences among observers. Figure 5 shows the average OMM and inter-OM Color Difference Metric (inter-MCDM) for all combinations involving a specific display, calculated using CIE 2006 10°. The results indicate that laser projectors induce greater color inaccuracies for both individual and group perceptions. However, these color inaccuracies caused by narrow-band displays are not as pronounced as predicted in previous studies [1][12]. Several potential reasons for this are: 1. This phase of the experiment only used white points as target colors, and the performance of OMM and inter-MCDM under other colors remains unknown; 2. In addition to the bandwidth of primaries, their peak wavelengths also affect the degree of OM. The varied peak wavelengths of the displays in this experiment mask differences in bandwidth; 3. Actual experiments introduce more noise than the simulation experiments, weakening such differences.

To test these hypotheses, a simulation experiment was designed using data obtained from this experiment. The principle

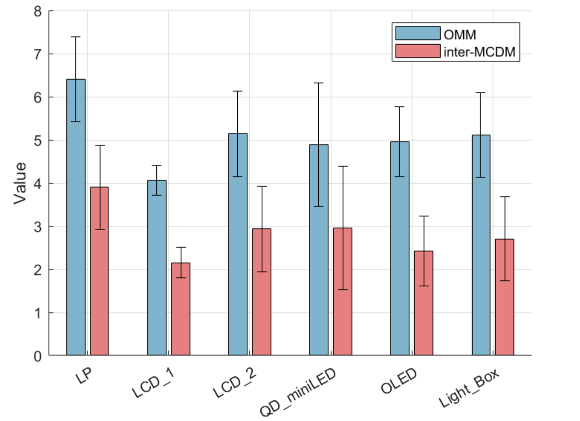


Figure 5. *OMM and inter-MCDM of 6 displays, mean and Std. are on the display combinations*

of the simulation experiment is as follows: Firstly, Multiply the CMF (3xN) by the SPD (Nx3) of the display's three primaries at certain normalized RGB values to obtain the XYZ response (3x3) of the CMF to the display's primaries. Given a target XYZ value (3x1), multiply this XYZ by the inverse of the XYZ response matrix (3x3) to obtain a set of RGB values (3x1). Multiplying these RGB values by the SPD (Nx3) at normalized values yields the SPD (Nx1) that achieves the desired XYZ response. Inputting multiple displays provides a "perfect observer" without matching errors and a "perfect display" without crosstalk, with infinite bit depth. Secondly, using experimentally obtained individual CMFs as simulated observers, modify their peak wavelengths and full width at half maximum (FWHM) based on the display SPD used in the experiment to create simulated displays and conduct simulated color matching experiments.

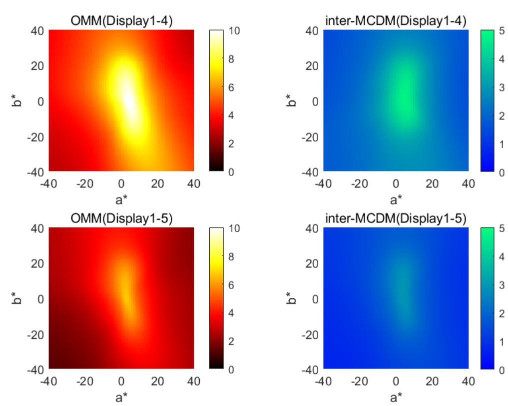


Figure 6. *OMM and inter-MCDM of display1-display4 and display1-display5 on a*b* plane*

Based on Hypothesis 1, using D65 with 150 nits as the white point, L* = 100 was set, and OMM and inter-MCDM were computed for a* and b* ranging from -40 to 40. This was done using Display 1 (LP), Display 4 (QD_miniLED), and Display 5 (OLED) as combinations, with Displays 4 and 5 serving as references. CIE 2006 10° was used for reference display calibration and for calculating OMM and inter-MCDM in the simulation experiments. The results, shown in heatmap format in Figure 6, reveal higher OMM and inter-MCDM values at lower chroma levels. Addition-

Table5: OMM of all CMF/Observer

OMM of CMFs/Observers	1	2	3	4	5	6	7	8	9	10	MEAN ± STD
CIE1931 2°	10.12	10.77	12.00	10.71	11.15	11.67	12.45	10.28	10.13	11.62	11.09 ± 0.78
CIE1964 10°	6.61	5.36	4.46	4.86	5.92	4.78	5.88	5.80	6.16	5.32	5.51 ± 0.64
CIE2006 2°	6.41	6.92	8.84	7.40	8.42	8.09	8.76	6.08	7.29	8.30	7.65 ± 0.93
CIE2006 10°	6.62	5.17	3.66	4.78	5.09	3.96	5.02	5.85	5.87	4.72	5.07 ± 0.84
Asano_CAT1	6.52	5.14	3.99	4.57	5.58	4.19	5.47	5.60	6.02	5.09	5.22 ± 0.75
Asano_CAT2	6.58	5.43	3.95	5.88	4.86	4.65	4.28	6.46	5.86	4.40	5.23 ± 0.89
Asano_CAT3	8.76	7.87	8.15	7.86	9.31	7.89	9.31	7.00	8.89	8.77	8.38 ± 0.71
Asano_CAT4	8.35	6.90	5.01	6.76	5.90	5.47	6.05	7.59	7.54	6.13	6.57 ± 0.99
Asano_CAT5	6.30	4.90	4.27	4.73	6.26	4.18	5.50	5.23	6.30	5.11	5.28 ± 0.76
Asano_CAT6	7.78	6.45	5.30	5.86	6.76	5.46	6.68	6.84	7.27	6.41	6.48 ± 0.73
Asano_CAT7	5.36	4.60	3.33	5.11	4.13	4.06	3.49	5.73	4.58	3.45	4.38 ± 0.80
Asano_CAT8	7.88	7.04	7.52	6.85	8.50	7.32	8.70	6.52	8.01	8.06	7.64 ± 0.68
Asano_CAT9	6.94	5.47	3.68	5.79	4.87	4.38	4.47	6.45	6.16	4.50	5.27 ± 1.00
Asano_CAT10	11.04	10.45	10.74	10.35	11.55	10.66	11.86	9.53	11.09	11.19	10.85 ± 0.63
Ko_CMF7	4.56	4.12	3.62	5.29	5.76	3.97	3.24	5.4	4.24	3.39	4.36 ± 0.83
Individual CMF	2.05	2.59	2.09	2.98	3.26	2.46	3.74	2.61	2.21	2.69	2.67 ± 0.51

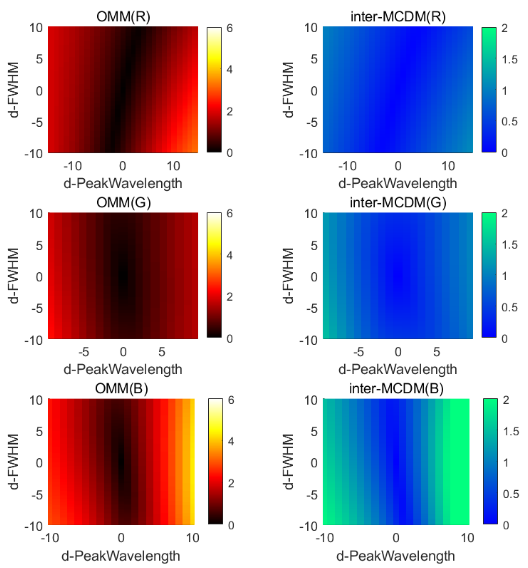


Figure 7. OMM and inter-MCDM of display4(offset)-display4(original) on d-FWHM and d-Peak wavelength

ally, significant contrasts between the two groups of displays were observed, higher than actual experimental data comparisons (OM for combination 1-4 was 7.31, and 1-5 was 5.04), aligning with Hypothesis 3, which suggests that perfect matching without noise accentuates differences between displays. Additionally, display 4 and 5 exhibit significant bandwidth differences compared to display 1. However, the peak wavelength of display 5 is very close to that of display 1. According to Hypothesis 2, this may be the reason for the smaller OM of the monitor 1-5 combination.

Regarding Hypothesis 2, using D65 with 150 nits as the white point and target color, the standard deviations for peak wavelengths and full width at half maximum (FWHM) for the five displays in this experiment were referenced: R: 10.0, 31.0; G: 6.4, 10.3; B: 6.9, 5.4. Peak wavelength offsets were set at 1.5 times the standard deviation, and FWHM offsets at 10 (the FWHM offset standard deviation for the R channel was too large for most displays). The modified simulated Display 5 was used as the matching display, with the original Display 5 as the reference. CIE 2006 10° was used for reference display calibration and for calculating CMF for OMM and inter-MCDM in simulated color matching experiments. The results, shown in heatmap format in Figure 7, indicate that, in terms of the selected primaries and offset scales in the experiment, peak wavelength has a far greater impact on OMM and inter-MCDM than bandwidth. The simulation results support Hypothesis 2, showing that blue primaries are more sensitive to offsets. Different primaries exhibit varying sensitivity to different offset directions, suggesting the potential to find an optimal peak wavelength that minimizes sensitivity to offsets from other primaries' peak wavelengths.

Conclusion

This study introduced a customized apparatus and experimental protocol specifically for investigating display metamerism and conducted initial color matching experiments with 10 participants. Experiment 1 involved 11 combinations formed from 6 different display devices, using white as the displayed color. The results were used to compare the performance of various CMFs in terms of OM. The findings demonstrated that the optimal choices among categorical observers consistently outperformed the best CIE 2006 10° standard observer(see Table5). Individual observers also showed superior results compared to categorical observers across all 10 participants, with an overall significant improvement.

Analysis of display primaries revealed that at the tested D65 white point, peak wavelength influences metamerism to a far greater extent than bandwidth. Additionally, the choice of reference colors had a significant impact on metamerism, with more pronounced effects observed in neutral color regions. The OM indices used in this study were based on the (ΔE_{00}, and whether this model aligns with color matching results under higher saturation colors remains to be validated.

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Author Biography

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Ronnier is a Professor at the College of Optical Science and Engineering, Zhejiang University (China). He was ExVicePresident and Ex-Director of Division 1 (Colour and Vision) of International Commission of Illumination (CIE). His main research areas include colour science, imaging science and LED illumination. He has published over 650 scientific papers. He is a Fellow of the Society for Imaging Science and Technology (IS&T), and the Society of Dyers and Colourists (SDC). He was the recipient of AIC 2017 Judd Award for lifetime achievement, and of 2020 Newton Award for outstanding contribution to colour science from the Colour Group of Great Britain.