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Individual Color Matching Functions and Application in Cross-media Color Reproduction

***Siyuan Song*[1]*, Ming Ronnier Luo*[1*]*, Tingwei Huang*[2]*, Andrew Rider*[3]*, Andrew Stockman*[1,3]**
[1] ***State Key Laboratory of Extreme Photonics and Instrumentation, Zhejiang University, Hangzhou, China.***
[2] ***THOUSLITE Light Lighting (Changzhou) Ltd; Changzhou, China.***
[3] ***University College London Institute of Ophthalmology, EC1V 9EL London, UK.***
****Corresponding author: Ming Ronnier Luo, m.r.luo@zju.edu.cn***

Abstract

In this study, two experiments were conducted to assess the importance of using individual color matching functions (CMFs) for cross-media color reproduction. Firstly, five observers used a visual trichromator to perform a series of color matches. Using the extended CIEPO006 model, these matches were used to derive estimates of each individual's CMFs. Each observer repeated the experiment five times to assess intra-observer variability. Subsequently, the same observers performed cross-media color reproduction experiments using a cross-media color matching system. The findings indicated that the individual CMFs can provide much more accurate predictions of the visual results than the standard CIE CMFs. Thus, individual CMFs can greatly enhance the accuracy of color reproduction.

Introduction

Human color vision varies between observers because of individual differences in macular and lens optical densities, photopigment optical densities and spectral shifts in the underlying cone photopigment spectra [1]. These differences result in individual differences in the shapes of the long-, middle- and short-wavelength (L-, M- and S-) cone spectral sensitivities (measured with respect to light entering the eye). These functions are also known as the cone fundamental LMS color matching functions (CMFs). Other CMFs, such as XYZ or RGB, which are linear transformations of the LMS CMFs, and thus manifest the same individual differences, but the differences are much harder to interpret and model without reference to LMS. Before the CIE 2006 standards, the standard 2° and 10° colorimetric observers defined by the CIE to represent the average observer were defined in terms of XYZ (or RGB) CMFs. The CIE 1931 2° standard colorimetric observer was based upon the data accumulated by Guild (1931) [2] and Wright (1929) [3, 4] and constructed using the flawed $V(\lambda)$ function [1]. The CIE 10° 1964 standard colorimetric observer was based on color matching measurements made by Stiles & Burch (1959) [5], and the likely rod-contaminated data of Speranskaya (1959) [6]. The rapid development of display and projector technology, including the use of spectrally narrow-band lights, makes these two standard colorimetric observers unable to meet new application requirements, because neither can be easily modified to account for individual differences. Moreover, the flaws in the 1931 observer can lead to large errors in color reproduction even before individual differences are taken into account [7, 8]. Recent research has shown that using the inappropriate 2° and 10° standard color matching functions may result in more pronounced observer metamerism on display [9].

In 2006, the CIE adopted the TC 1-36 committee's proposal for a new physiological observer model (CIEPO06), which includes a standard LMS and RGB observer for 2° and 10° that can be adjusted for individual differences [10]. The CIEPO06 model is almost entirely based on the work of Stockman & Sharpe [11]. Starting from 10° RGB CMFs of 47 Stiles & Burch observers [5], the model defines 2° and 10° fundamental observers and provides a convenient framework for calculating average cone fundamentals for any field size between 1°and 10° and for any age between 20 and 80 years. In 2015, the CIE adopted a transformation from CIEPO06 LMS to XYZ [12]. The CIEP006 model has recently been extended by Stockman and Rider [13], who defined the CMFs and optical density spectra as continuous functions of wavelength, extended the wavelength range from 390 to 830 nm to 360 to 850 nm for all three cones, incorporated shifts in the spectral positions of the L- and M-cone photopigments and corrected a small error in the shapes of the original functions between 390 and 400 nm. This extended model, with just 7 parameters, greatly facilitates computation and curve fitting, is taken advantage of here.

In 2008, Oicherman studied the individual variability of cross-media color reproduction between LCD displays, with relatively broadband primaries, and object color stimuli and found observer metamerism was insignificant for all colors except neutrals [14]. However, recent technological advances that use spectrally narrow primaries to produce wide color gamut displays (e.g., LEDs, OLEDs, lasers, and Quantum Dots) have possibly made the problems with observer metamerism far worse and worth revisiting [15]. A potential solution to this problem is to personalize the color reproduction for individual observers [16]. In this study, we compare various CIE standard CMFs, including 1931 2° CMFs, 1964 ° CMFs, 2006 2° and 10° CMFs as well as individualized CMFs to predict metamerism.

Experiments

Two experiments were conducted in this study. In the first experiment, observers used a visual trichromator to perform color matching so that individual CMFs could be calculated. In the second experiment, the same observers performed cross-media color matching. This cross-media color reproduction experiment was used to test the performance of CIE CMFs and individual CMFs in predicting the matches.

Apparatus

LEDMax

In this study, a multi-primary visual trichromator named LEDMax® was used to estimate each individual's LMS fundamental CMFs. The experiment setup is shown in Figure 1. This trichromator has been used and described in previous studies [17–19]. Briefly, a matching half-field and a reference half-field were illuminated by separate LED cubes, each of which contained 18 LEDs with different peak wavelengths. The half-fields were abutting semi-circles making a circular stimulus with either a 2° or a 10° field of view (FOV). A fixed triplet of lights produced the white reference field on the right side with luminance of 120 cd/m^2 and color temperature of 7500°K. We used 13 of the LEDs in various combinations to form 11 different triplets of lights in the matching half-field , listed in Table 1. After color characterisation, we transformed the primaries into CIELAB color space, and the observer was asked to vary L* (lightness), a* (redness-greenness), b* (yellowness-blueness) to match the reference white.

Table 1.The 11 different triplets of lighs in the mixture half-field

Primary sets	R (nm)	G (nm)	B (nm)
1	640	530	430
2	640	530	445
3	640	530	460
4	640	530	475
5	640	505	445
6	640	560	445
7	640	545	445
8	595	530	445
9	605	530	445
10	660	530	445
11	675	530	445

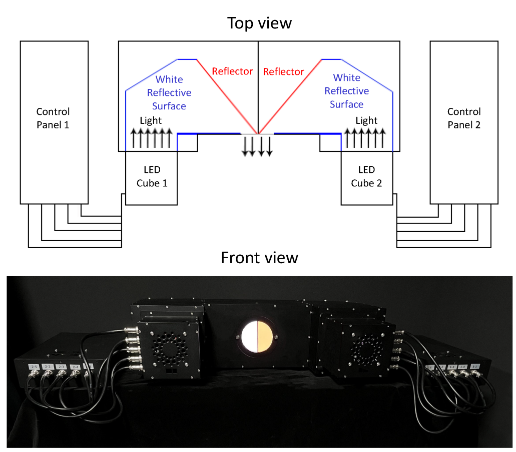

Figure 1. The structure and appearance of the LEDMax

LEDSimulator

A system made by the Thouslite, called LEDSimulator® was used. It is designed as a color appearance communication system in surface industries such as textiles, printing, inks, etc. The asymmetric color matching technique is used to reproduce the "Total Appearance" including texture and translucency, cross media including a physical and a virtual sample.

LEDSimulator includes LED lighting systems [20]. The one in front is a viewing cabinet (LEDView®), which provides standard viewing conditions to accurately simulate CIE D65, D50 or A illuminants. The color sample to be matched is placed in this cabinet. In the rear of the cabinet, two light panels (LEDPanel®) form a backlighting system that includes red, green, and blue lights illuminating a textured white substrate, with peak wavelengths of 631 nm, 537 nm, and 471 nm, respectively. Figure 2 shows the front view and back view of LEDSimulator, respectively. In essence, a colored sample is viewed under white lighting in the front cabinet and this is matched to a neutral sample that is back-illuminated by colored lights in the rear of the cabinet behind the samples.

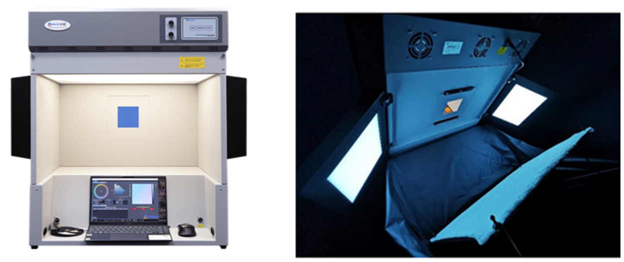

Figure 2. The front view and back view of LEDSimulator

In the present cross-media color reproduction matching experiment, observers matched 15 color samples and neutral paint samples (including 13 Coloro® cloth samples plus 2 NCS cards [21]). The samples were devoid of any perceptible grain, gloss, or fluorescence, and exhibited no visible signs of wear or wrinkling. Figure 3 shows these colors in a*b* plane. Each observer repeated the experiment 3 times, the repeats were used to assess intra-observer variability.

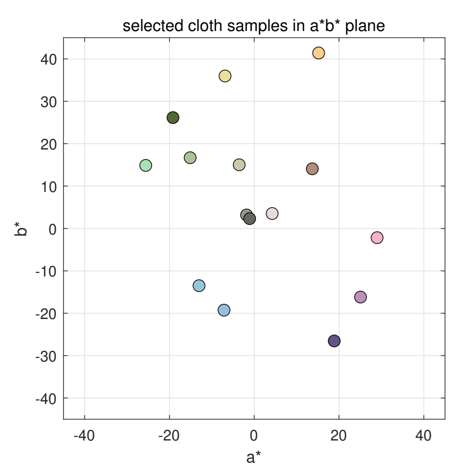

*Figure 3. The 15 color samples in a*b* plane (calculated using CIE 2006 10° CMFs). The color of each circle approximates the sample's appearance.*

Observers

Five male observers participated in this experiment with a mean age of 24 years. All five observers successfully passed the Ishihara color vision test. They repeated the color matches in the LEDMax experiment five times, and their matching results confirmed that they are color normal. All the observers had the background knowledge of color science.

Procedure

Observers performed the LEDMax color matching experiments first and then the cross-media color matching using LEDSimulator.

The LEDMax color matching experiment was conducted in a darkened environment to which the observers adapted for 2 minutes prior to the experiment. A chin rest was used to fix the observer's position at 50cm away from the viewing fields. All observers were trained by doing a complete set of experiment, i.e. they did 11 color matches with a 10° FOV firstly and then did 11 color matches with a 2° FOV. Over the next five days, observers conducted the formal experiments, repeated the experiment once every day. At the beginning of each experiment, observers were adapted to the testing environment for two minutes, after which they began to make color matches with a FOV of 10°, until 11 matches were completed. After a brief rest of 10-15 minutes and re-adaptation, the observer completed a further 11 color matches with a 2° FOV. For one repetition, each observer had to perform 22 color matches, which took on average about 70 minutes. During the experiment, the order of matching triplets presented were randomized.

After finishing the LEDMax color matching experiment, observers did the cross-media color reproduction experiments using the LEDSimulator. The observers' position was not constrained, so they could move between 60 and 70 cm from the fields. The lighting of LEDSimulator was a D65 simulator at 500 lux. Observers placed the samples on the right side of the viewing window and made the width of the left side consistent width of the Coloro® samples, about 5 cm, while the FOV ranged from 8° to 9.5°. They used the CIELAB L*a*b* or $L^*C_{ab}^*$ h controls to adjust the colors on the left to achieve cross-media color matching. After completing a set of 15 matches, they rested for 10-15 minutes and then moved on to the next set until all the matches were completed. Figure 4 illustrated the cross-media color reproduction experiments environments.

Figure 4. The cross-media color reproduction experiments environments.

Each of the five observers completed the 155 color matches. Each observer did 110 matched with LEDMax: 11 color matches to the white standard with five repetitions for two FOVs, and 45 color matches in the cross-media color reproduction experiment: 15 matches with three repetitions. It took 70 minutes for one repeat of the LEDMax experiment and 40 minutes for one repeat of the cross-media color matches.

Results

The spectral power distributions (SPDs) of all the matching half-field and the white reference standard of the LEDMax were measured using a JETI 1211 spectroradiometer imaged in the same position as observer's eye. All SPDs are multiplied by the observers' glasses transmittance to avoid potential impacts. The SPDs for all the lights that the observer matched the white standard were used to estimate the individual LMS cone spectral sensitivities (or LMS fundamentals) for each observer. For more details see our previous papers [17–19]. XYZ CMFs for each observer could then be linearly transformed from their LMS fundamental CMFs [12]. Similarly, the SPDs of cloth samples and matched lights of LEDSimulator cross-media color reproduction experiment were also measured. Note the latter served as an independent test set to verify the performance of CIE standard CMFs and individual CMFs.

Observer variation

The matching SPDs were tansformed to XYZ tristimulus values using the CIE 2006 2° or 10° CMFs and further transformed to CIELAB color space. For each observer, the Mean-Color-Difference-from-the-Mean (MCDM) [22] was used to show the intra-observer variation as shown in Table 2. Similarly, the inter-observer MCDM was also calculated, for which 2° and 10° are 3.55 and 2.04, respectively. Since the intra-observer variability is significantly smaller than the inter-observer variability, it suggests clear difference between the 5 observers even though they all have normal color vision.

Table 2. Intra-observer variation of LEDMax color matches as CIEDE2000 color difference [23]

	obs 1	obs 2	obs 3	obs 4	obs 5	mean
2°	1.501	1.455	1.813	1.924	0.989	1.536
10°	0.953	1.055	0.961	1.242	1.079	1.058

In the cross-media color matching experiment the intra-observer variability was smaller than that in the LEDMax color matching experiment and is listed in Table 3. The inter-observer variation is 2.12, close to inter-observer variation MCDM of the 10° color matching experiment.

Table 3. Intra-observer variation of cross-media color reproduction as CIEDE2000 color difference

obs 1	obs 2	obs 3	obs 4	obs 5	mean
0.737	0.491	0.491	0.767	0.627	0.623

Deriving individual color matching functions

The extended CIEPO06 model developed by Stockman & Rider [13], has 11 physiological parameters that are expected to account for any individual differences in the CMFs. Three parameters were fixed across FOV - lens density and the spectral shifts of the L and M cones – while four others varied - macular density, and the L-, M- and S-cones photopigment densities. We fitted this model by optimizing the parameters to minimize the difference in cone excitation values between the reference half-field and the matching half-fields.

The Table 4 shows the mean and standard deviation of the parameters obtained from five repeat matches for each observer. The results showed that our CMFs parameters are stable, it can be observed that the macular densities of the individual observers are higher, and the M cone are slightly shifted toward the long-wave direction, which is consistent with our previous finding [18, 19].

Comparing the predictions of the CMFs in LEDMax matches

The performance of the observer's individual color matching functions in predicting the white matches is compared with the predictions of the standard CIE 1931 and CIE 2006 2° CMFs, and the CIE 1964 and CIE 2006 10° CMFs. Previous study show that there was little difference in terms of CIEDE2000 color difference calculated using different CMFs [24]. Figure 5 shows the matching errors calculated under different CMFs. The individual matching errors are shown as symbols, while the bars and error bars show the means and standard deviations. The left-hand and right-hand plots shows the 2° and 10° fits, respectively. As expected, the 2° and 10° individual CMFs perform best for the 2° and 10° matches, respectively. For the 2° matches, only observer 2's errors (rightward pointing triangles) did not show improvement compared to the CIE2006 CMFs. Observers 2 and 4 did not show much improvement in the 10° matches. Overall, individual CMFs consistently outperform standard ones, although this should be expected when comparing an 11-parameter model with a fixed (parameter free) model.

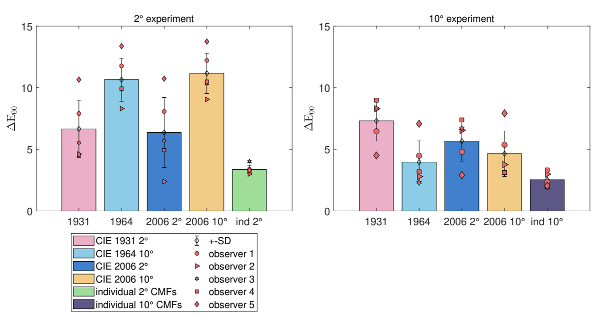

Figure 5. *The performance of different CMFs in LEDMax experiment*

We also compare our results by plotting them on a chromaticity diagram. Using appropriate CMFs all the matches should, by definition, plot to the same point. Figures 6 and 7 show the 95% confidence tolerance ellipses for the color coordinates of the 11 triplets in a*b* space, calculated using different CMFs. Using individual CMFs not only brings the ellipse center closer to the reference but also results in a significantly smaller ellipse compared to using CIE standard CMFs.

Comparing the predictions of the CMFs in cross-media color reproduction

Although the matching procedures, samples and matching lights and the experimental environment used in the second experiment are different from those of the first one, the results will still depend on the individual's CMFs. Therefore, if the individual CMFs derived in the first experiment can predict results in the second experiment better than the CIE standards, it will further demonstrate their general utility.

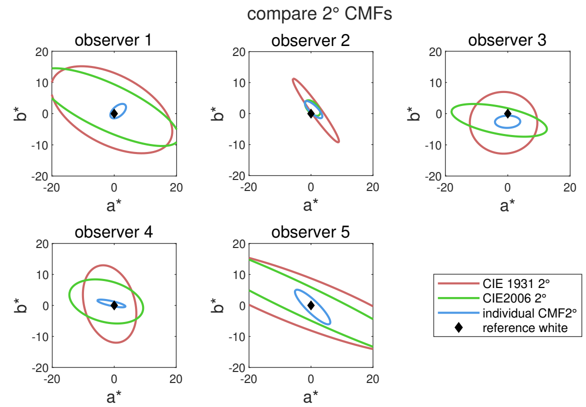

Figure 6. *95% confidence ellipses for 11 triplets in the 2° experiment, calculated using CIE 1931, CIE 2006, and each observer's mean 2° CMFs*

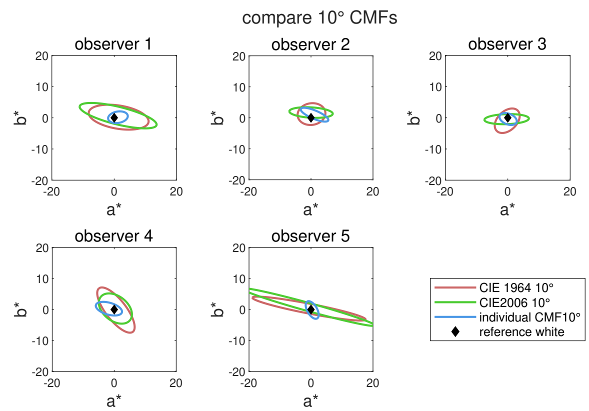

Figure 7. *95% confidence ellipses for 11 triplets in the 10° experiment, calculated using CIE 1964, CIE 2006, and each observer's mean 10° CMFs*

The color difference between the cloth sample and the matched light using different CMFs was calculated to test the ability of different CMFs to predict the visual results of cross-media color reproduction. We took the average of each individual's three repeats for each sample to represent the final results. Encouragingly, the individual CMFs always performed best, and for most observers, the 1931 2° CMFs performed the worst, similar to previous results [7,8]. The color difference results are shown in Table 5.

Figure 8 shows of the performance of CMFs for each observer. Individual 10° CMFs performed the best for three observers, which makes sense as the cloth samples were bigger than 2°, but for Observers 2 and 5, 2° individual CMFs performed the best. Notice that CIE 1964 and CIE 2006 10° are often similar because both are derived from Stiles & Burch 10° CMFs. It is interesting to note that observers who performed best with 2° individual CMFs also performed well with CIE 2° CMFs, while observers who performed best with 10° individual CMFs also performed well with CIE 10° CMFs compared to 2°.

Figure 8 showed that for most of the observers, individual

Table 4. Mean and standard deviation of model parameters fitted to the color matches for each observer. The standard values are from CIEPO06 model [10].

	Lens	Mac 2°	L-od 2°	M-od 2°	S-od 2°	L-shift	M-shift	Mac 10°	L-od 10°	M-od 10°	S-od 10°
obs 1	1.362 ± 0.109	0.698 ± 0.004	0.368 ± 0.035	0.418 ± 0.100	0.342 ± 0.014	1.321 ± 1.361	4.076 ± 1.030	0.152 ± 0.019	0.323 ± 0.107	0.423 ± 0.078	0.397 ± 0.098
obs 2	1.507 ± 0.138	0.425 ± 0.031	0.580 ± 0.064	0.591 ± 0.065	0.445 ± 0.092	-0.596 ± 0.733	-2.217 ± 0.948	0.188 ± 0.004	0.519 ± 0.034	0.422 ± 0.105	0.341 ± 0.071
obs 3	1.550 ± 0.065	0.482 ± 0.069	0.306 ± 0.010	0.349 ± 0.089	0.300 ± 0.000	0.006 ± 1.598	4.601 ± 1.200	0.069 ± 0.005	0.329 ± 0.028	0.277 ± 0.025	0.280 ± 0.035
obs 4	1.240 ± 0.005	0.575 ± 0.057	0.550 ± 0.104	0.503 ± 0.135	0.308 ± 0.016	-3.254 ± 2.530	1.597 ± 1.413	0.123 ± 0.042	0.473 ± 0.091	0.588 ± 0.118	0.339 ± 0.077
obs 5	1.434 ± 0.094	0.700 ± 0.000	0.506 ± 0.144	0.337 ± 0.053	0.665 ± 0.070	0.165 ± 1.577	5.299 ± 1.461	0.134 ± 0.043	0.412 ± 0.094	0.304 ± 0.058	0.537 ± 0.084
standard	1.765	0.350	0.500	0.500	0.400	0.000	0.000	0.095	0.380	0.380	0.300

Table 5. The color difference values of cross-media color reproduction experiment using different CMFs. The results in GREEN and RED mean the best and worst performed CMFs, i.e. gave the smallest and largest color differences respectively.

	1931 2°	1964 10°	2006 2°	2006 10°	Mean ind 2°	Mean ind 10°
obs 1	6.926	3.614	3.417	3.839	3.604	2.336
obs 2	4.893	2.102	1.956	2.749	1.877	2.489
obs 3	6.715	1.781	3.479	1.794	3.354	1.070
obs 4	6.356	2.447	3.897	2.198	3.164	1.956
obs 5	2.357	4.382	2.027	5.128	1.532	2.392
mean	5.450	2.865	2.955	3.142	2.706	2.049

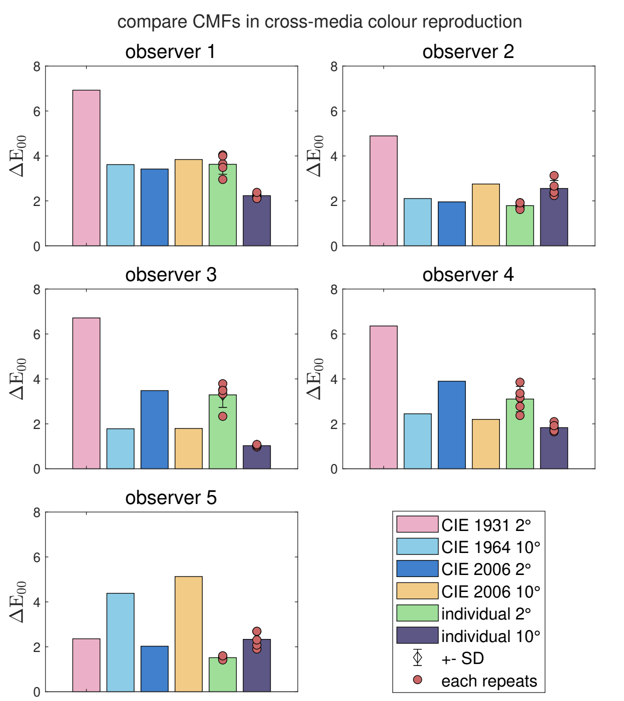

Figure 8. *Summary the performance of different CMFs' performance in cross-media color of each observer*

CMFs greatly reduce the metamerism in cross-media color reproduction matching differences by 50.3% and 28.5% compared to the CIE 1931 2° and 1964 10° matching results. In maximum, individual CMFs can reduce color difference of about 60%.

Finally , the 15 colors conducted in the cross-media matching experiment were presented in terms of 95% color discrimination ellipses to show different CMFs' performance, as shown in Figure 9. When using each set of CMFs, there will be a pair of color coordinates for the cloth and the light. For clarity, we have aligned the cloth's color coordinates from different CMFs with those from the 2006 10° CMFs and shifted the matches and the 95% confidence ellipses across the 5 observers by the same amount. Using individual CMFs, not only is the centers of the ellipses closer to the cloth samples, but the ellipse are significantly smaller than using CIE standard CMFs.

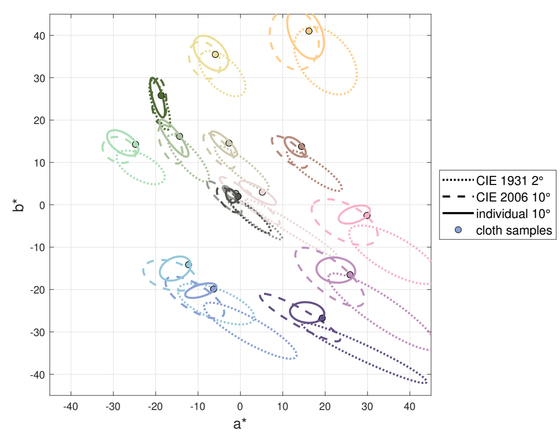

Figure 9. *Comparing different CMFs' performance of 15 color samples in a*b* plane. The dotted, dashed, and solid lines represent the CIE 1931 2° CMFs, the 2006 10° CMFs, and the individual 10° CMFs, respectively. The color of each circle approximates the sample's appearance.*

Conclusion

Five observers made color matches using LEDMax and repeated the matches five times from which their individual cone fundamentals and XYZ CMFs were derived. Subsequently, they used the LEDSimulator to perform cross-media color matches, with each observer repeating the matches three times. The analysis of intra-observer and inter-observer variability revealed the presence of distinct observer metamerism even though the five observers had normal color vision. The individual CMFs agreed with those from previous studies in showing that our observers generally have higher macular pigment optical densities and M-cone spectral sensitivities that shifted slightly towards long-er wavelengths compared to the CIE standard. The 1931 CIE standard observer CMFs exhibits the poorest performance in predicting both color matches and cross-media color reproduction tasks. The color matching functions based on the CIE 2006 cone fundamentals are more representative of the average observer; but the use of individual CMFs can enhance the accuracy of color reproduction.

The individual CMFs obtained from this study generally outperformed the CIE standard CMFs and exhibited a 33.3% reduction in color differences in cross-media color reproduction compared to the CIE standard CMFs. Although color matching differences are generally expected to be more significant for narrowband light sources, the matches with broadband reflected light from the color samples supports the general applicability of the CMFs derived using the LEDMax system and their potential for improvements in various cross-media color reproduction scenarios and personalized imaging. Our future research will focus on efficiently and accurately deriving individual CMFs and incorporating them into real-world industrial applications.

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Author Biography

Siyuan Song received his BS in Optical Engineering from Ocean University of China (2023) and has been a Master student supervised by Professor Ming Ronnier Luo at Zhejiang University since 2023. His research work is on individual color matching functions and its application.