Received: 14 October 2023 | Revised: 12 March 2024 | Accepted: 18 March 2024

DOI: 10.1002/col.22928

RESEARCH ARTICLE

COLOR RESEARCH AND APPLICATION WILEY

A multi-primary trichromator to derive individual color matching functions and cone spectral sensitivities

Keyu Shi[1] | **Ming Ronnier Luo**[1] | **Andrew T. Rider**[2] | **Tingwei Huang**[3] | **Lihao Xu**[4] | **Andrew Stockman**[1,2]

[1]State Key Laboratory of Extreme Photonics and Intrumentaion, Zhejiang University, Hangzhou, China

[2]University College London Institute of Ophthalmology, University College London, London, UK

[3]Thousand Lights Lighting (Changzhou) Limited, Changzhou, China

[4]School of Digital Media and Art Design, Hangzhou Dianzi University, Hangzhou, China

Correspondence
Ming Ronnier Luo, State Key Laboratory of Extreme Photonics and Instrumentation, Zhejiang University, Hangzhou, China.
Email: m.r.luo@zju.edu.cn

Funding information
National Natural Science Foundation of China, Grant/Award Numbers: 61775190, 62305096; BBSRC, UK, Grant/Award Number: BB/R019487/1

Abstract

Measuring color matching differences between observers is an important means of investigating individual differences in human color vision. In this article, we introduce a new LED-based visual trichromator with which we have estimated color matching functions and cone spectral sensitivities in a group of five normal observers. The trichromator has side-by-side semi-circular matching fields that are illuminated by two spectrally tunable LED light sources, each comprised of 18 LEDs with center wavelengths ranging from 400 to 700 nm. We used Maxwell's method to derive a set color match. A fixed triplet of red-green-blue (RGB) primaries produced the white standard field of 120 cd/m^2 in one field. The other field, the mixture field, was illuminated by one of 11 different triplets of lights with various center wavelengths. Observers adjusted the intensities of the triplets in the mixture field to match the white standard field. All matches were made for field diameters of 2° and 10° of visual angle to allow comparisons with colorimetric standards and were repeated five times. Calibrations and tests showed that the trichromator and the measurements were stable and repeatable. Grassmann's laws predict that at the 11 color matches the excitations in the three cone types should be the same. Consequently, we can use those matches and a model of how cone spectral sensitivities vary between individuals to estimate the three underlying corneal cone spectral sensitivities for each observer (and thus how they vary from the standard (or mean) observer). We find good agreement with the CIE 2006 standards, but our observers show small but consistent differences.

KEYWORDS
color matching functions, cone fundamentals, multi-primary trichromator

JEL CLASSIFICATION
D8

1 | INTRODUCTION

Human color vision depends on the responses of three classes of photoreceptor (cones) each of which has a different spectral sensitivity (sensitivity measured as a function of wavelength). The three classes are known as long-wavelength- (L-), middle-wavelength- (M-), and short-wavelength- (S-) sensitive cone types according to the part of the visible spectrum in which they are most sensitive. Because cone responses are univariant (i.e., the response to absorbed photons are independent of photon wavelength), the cone spectral sensitivity functions can be used to calculate the relative cone responses to a light of a given spectral power distribution (SPD). Very simply, each cone spectral sensitivity can be cross-multiplied by the SPD of the light, wavelength by wavelength, and summed to give three values: the L, M, and S responses to that light. Lights with different SPDs that appear identical (i.e., they are color matches) should all produce the same three cone responses. However, cone spectral sensitivities can vary, even among color normal observers, so that white lights that produce a color match for one observer may appear dissimilar to another. Here we invert this process to estimate the L-, M-, and S-cone spectral sensitivities for individual observers from their color matches. Essentially, we ask observers to find a series of white lights made up of different triplets of lights that all match the same standard white, and then fit a parametric model to find the three cone spectral sensitivities for which the matched white SPDs generate the most similar cone responses. The model features seven parameters that account for individual differences in cone spectral sensitivities caused by: spectral shifts in the L- or M-cone spectral sensitivities (two parameters); variations in the L, M, or S photopigment optical densities (three parameters); and differences in the opacities of the lens and macular pigment in the eye (two parameters) (for review see Ref. 1). Webster and MacLeod[2] used a related model to analyze the individual differences in the Stiles and Burch 10-deg color matching data.[3] Asano, Fairchild and Blondé[4,5] also examined at the population level whether random, but representative, variations in these parameters via Monte Carlo simulation might account for the variability seen in color matching functions.

While color appearance can vary between observers, the constraints of color specification and reproduction requires a common framework. Much effort has been expended on defining the standard or mean LMS cone spectral sensitivities (or their linear transformations, the XYZ or RGB color matching functions (CMFs)) under 2° (small-field) and 10° (large-field) viewing conditions. The field size distinction is important as the macular pigment, which absorbs light in the shortwave end of the visible spectrum, is only present in the center of vision. The most widely used, but flawed.[1] CMFs are the CIE 2° 1931 color matching functions, which are based on the relative color matching data of Guild[6] and Wright[7,8] and the CIE 1924 luminosity function V(λ). Over 30 years later, the CIE defined the large-field 10° CIE 1964 CMFs,[9] which are based mainly on color matches measured in 49 observers by Stiles and Burch,[3] but also incorporate the possibly rod-affected matches measured in 27 observers by Speranskaya.[10]

The 1931 CIE 2° and the 1964 CIE 10° CMFs are defined with respect to imaginary XYZ primaries and are referred to as the $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$ CMFs. The functions are tabulated in tabs. 1 (3.3.1) for the 2° and 1 (3.3.2) for the 10° in Wyszecki and Stiles[11] and they can also be found online in the CVRL database (www.cvrl.org). The 1931 CIE 2° and the 1964 CIE 10° CMFs are also tabulated for real RGB primaries, which are referred to as the $\bar{r}(\lambda)$, $\bar{g}(\lambda)$, and $\bar{b}(\lambda)$ CMFs. Tab. 1 (3.3.3) of Wyszecki and Stiles gives the 1931 2° CMFs for primaries of 435.8, 546.1, and 700.0 nm, while tab. 2 (3.3.3) gives the 1964 10° CMFs for primaries of 444.4, 526.3, and 645.2 nm.

The CIE standard observers have become important tools in color science, colorimetry, and color measurement, since they allow researchers and practitioners to quantitatively analyze and compare colors, define color spaces, and reproduce colors in various applications including imaging, printing, lighting, and display technologies. However, the rapid development of technology and the use of narrow-band spectral lights has made the 2° observer, in particular, unable to meet new application requirements without errors.[12–14] Another drawback is that the CIE 1931 and 1964 CMFs were never explicitly linked to the long- (L), middle- (M), and short- (S) wavelength cone spectral sensitivities, which are the "physiologically-relevant" fundamental CMFs upon which all color matches depend.

In 1991, the CIE established a technical committee (TC1-36) with the goal of defining a colorimetric standard observer that was linked to the cone fundamentals or cone spectral sensitivities, and that would correct some of the problems with the existing CIE standards. In 2006, the CIE adopted 2° and 10° LMS cone fundamentals that were based almost entirely on the work of Stockman, Sharpe and Fach[15] and Stockman & Sharpe.[16] They measured cone spectral sensitivities in dichromats (lacking either L- or M-cones), S-cone monochromats (lacking both L- and M-cones) and observers with normal color vision, all of known photopigment genotype, from which they defined the cone fundamentals as a linear combination of the 10° CMFs Stiles and Burch observers.[3] Their work also included estimates of the optical density spectra of the macular and lens pigments, the three photopigment spectral absorbance curves and the cone photopigment optical densities, all of which were incorporated in CIE 2006 2° and 10° standards.[17,18] The CIEPO06 model, provides a convenient framework for calculating cone fundamentals for any field size between 1° and 10° and for any age between 20 and 80. The CIEP006 model has recently been extended by Stockman and Rider,[19] 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, and corrected a small error in the shapes of the original functions between 390 and 400 nm. This new model, with just seven parameters, greatly facilitates computation and curve fitting, which we take advantage of here.

In this article, we introduce a new LED-based color matching device with which we ask observers to make color matches to a white reference using triplets of lights of eleven different wavelengths. We then analyze these matches using the CIEPO006 model to determine the cone fundamentals of each individual observer and thus the individual differences between them (see below). Several studies have obtained color matching data using devices with up to six primary lights produced either by optically combining cathode ray tube (CRT) and liquid crystal display (LCD) display devices or by using six LEDs of different wavelengths as well as broadband white LEDs.[20–23] The purpose of these studies was principally to investigate the effects of individual differences on cross-media color matches. In none of them were the matches used to estimate the cone fundamentals of individual observers. One exception was the study by Asano et al.,[24] but the analysis gave unexpected values for some individual differences, that is, L-cone spectral shifts to longer wavelengths and M-cone shifts to shorter wavelengths and macular densities that appear inordinately high.

We collected a series of color matches using 11 triplets of lights and two field sizes from which we were able to plausibly estimate the individual differences between observers and thus define individual cone spectral sensitivities. We found that to reliably estimate the parameters needed to define and generate individual cone fundamentals (lens and macular pigment densities, L- and M-cone spectral shifts and the L-, M-, and S-cone photopigment optical densities) required color matches to be made with at least 16 triplets of lights over two fields of view (FOV).

2 | EXPERIMENTAL METHODS

2.1 | Color matching methods

The most commonly used method for measuring color matches is known as the maximum saturation method. The method, which is illustrated in the upper panel of Figure 1, was used to derive both the CIE 1931 2° and 1964 10° standards.

In the maximum saturation method, the observer is presented with a half-field illuminated by a “test” light of variable wavelength (λ) and one of the red (R), green (G), or blue (B) primary lights, and a second half-field illuminated by the two remaining primary lights. The observer adjusts the intensities of the three primaries to make a match. A disadvantage of this method is that the color of the matched lights and thus the experimental conditions vary with test wavelength.

Maxwell's color matching method is another traditional but less frequently used method adopted by Maxwell in 1860 to obtain the first careful, quantitative color matching measurements.[25] In Maxwell's method, which is illustrated in the lower panel of Figure 1, the matched fields always appear white, so that at the match the eye is always in the same state of adaptation whatever the test wavelength (in contrast to the maximum saturation method in which match chromaticity varies with test wavelength). In the matching experiment, the observer is presented with a fixed white standard half-field (in our experiments made up of three primaries), and then asked to match it by adjusting the intensities of two primary lights and the test field in the other half-field. The test field is varied in wavelength and replaces one of the three primaries such that a match can be made to the white (we followed this protocol, see Table 2).

If color matching additivity holds,[26] there should be no difference between CMFs measured using the maximum saturation and Maxwell's methods, yet Crawford[27] showed that there were clear discrepancies (see his fig. 3). In particular, along the spectrum locus between Crawford's blue (460 nm) and green (530 nm) primaries, Maxwell's method requires more of the red (650 nm) and less of the blue primary to complete the match than if the maximum saturation method is used. Comparable discrepancies have been reported by Wyszecki in pilot data published in Wyszecki and Stiles[11] (see their figs. 4 (5.6.6) and 5 (5.6.6)) and later by Zaidi.[28] We chose to use Maxwell's method because the state of adaptation at the match is held constant. This may lead to small discrepancies with the CIEPO06 model between 460 and 530 nm, since the color data on which CIEPO06 is based obtained using the maximum saturation method.[3]

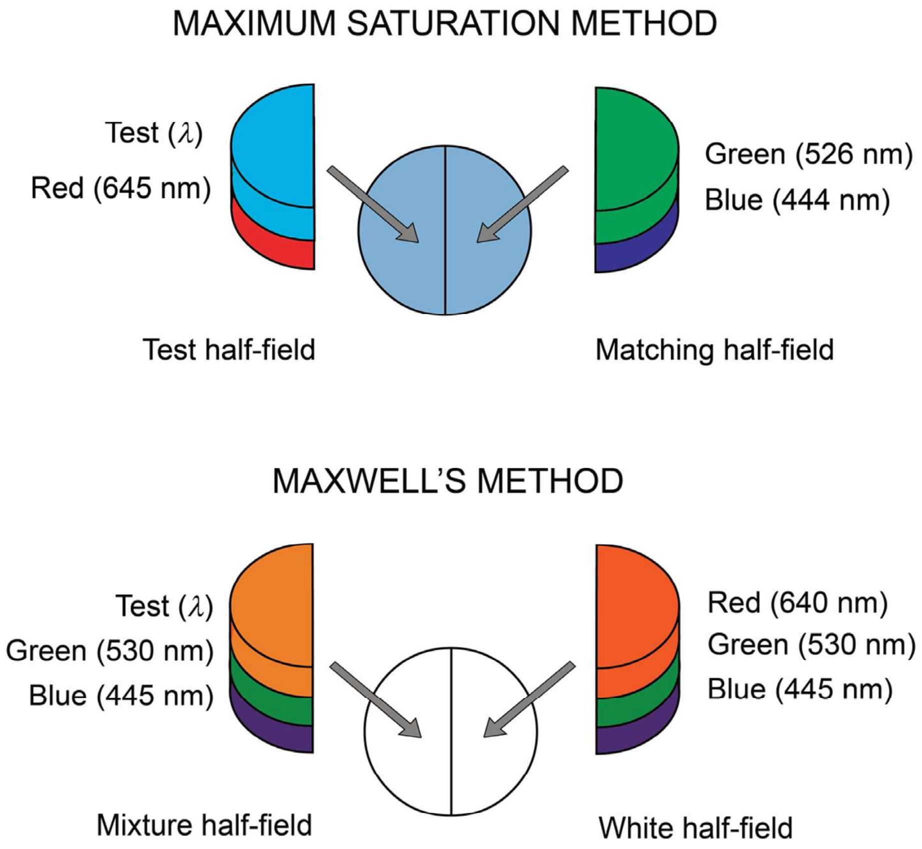

FIGURE 1 The maximum saturation method (upper) with the Stiles & Burch primaries and Maxwell's method (lower) with our primaries.

2.2 | APPARATUS

Various types of light sources in combination with spectral filters, prisms and/or diffraction gratings have been used to produce the primary and test lights used in color matching experiments.[3,7,27,29] Monochromators illuminated by intense light sources have been used before,[3] but these kinds of trichromators are typically very large and cumbersome. With the recent advances in LED technology, high-intensity LEDs with different peak wavelengths have become a practical alternative to conventional light sources.

Our study utilized a multi-primary visual trichromator to measure color matching, which we helped to design. The system is called LEDMax® supplied by Thouslite. The trichromator is composed of three parts: a control panel, two identical left and right LED Cube illuminators, and a viewing compartment. Each illuminator contains 18 LEDs with different center wavelengths ranging from 400 to 700 nm. The light emitted by the left and right multi-LED cube units each illuminate a white reflective surface in the viewing compartment, which then uniformly fills one of two side-by-side semi-circular apertures. Figure 2 shows a schematic diagram of the system and an image of its outward appearance showing the two side-by-side matching fields. The size of the fields was changed by replacing the aperture at the front.

As noted above, each cube contains 18 different LEDs with center wavelengths ranging from 400 to 700 nm (of which we used 13 for these experiments, the other 5 were excluded on the grounds that they were either too dim or at the far extremes of the visible spectrum). The spectral bandwidths or full width at half maxima (FWHM) vary with the center wavelength, as do their peak radiances and luminances (see Figure 3 and Table 1).

We conducted several tests to validate system performance. In one test, we monitored brightness changes in 13 channels over a period of 6 months to assess long-term repeatability, while in another test we monitored differences in the spectral power distribution between the two LED cubes. Detailed test information can be found in Table 1.

The spectral power distributions (SPDs) of the LEDs were measured using a Konica-Minolta CS2000 spectral radiometer. The repeatability was estimated by calculating the root mean square percent error (RMSE%) value between sets of measurements. We first calculated the SPDs data of an LED emitting light five times, and used the average SPD as the standard. We then normalized the peak value of this average to 1, and calculated the RMSE % value of the five-measurement data compared with this average as a reference for repeatability. The long-term repeatability of the system over 6 months was 0.52 RMSE

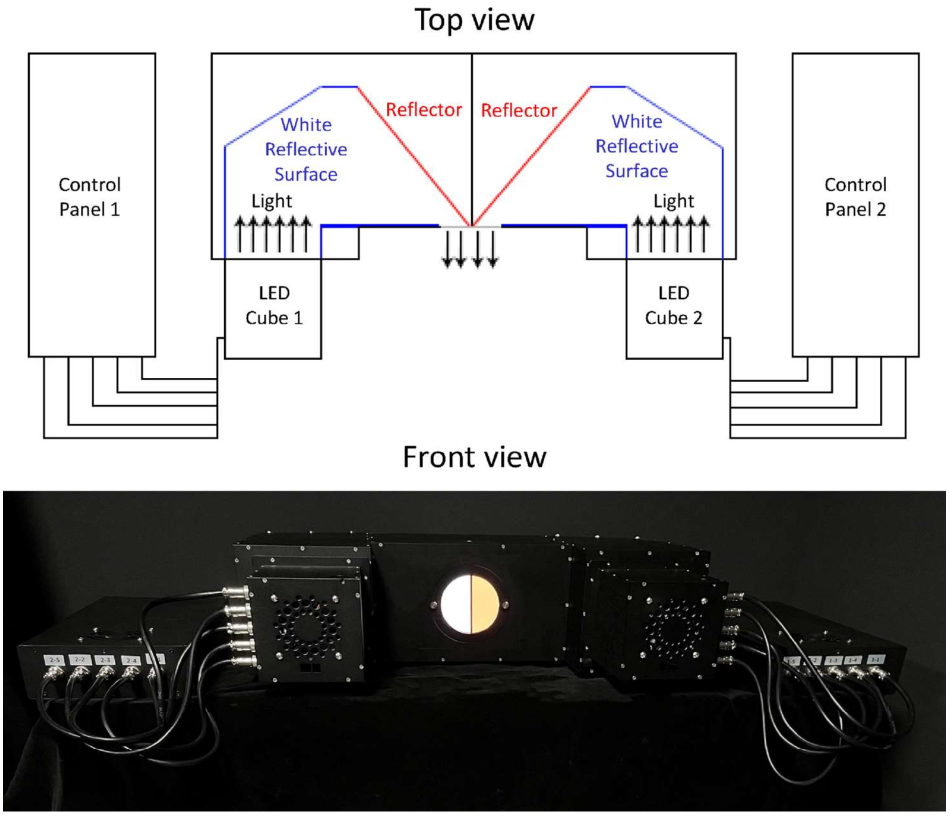

FIGURE 2 Above: The internal structure of the system. Below: Its outward appearance showing the bipartite matching fields.

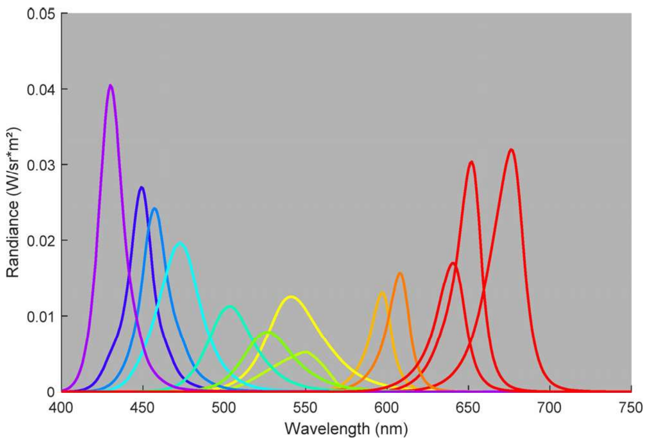

FIGURE 3 The spectral power distributions (SPDs) for 13 LEDs at their maximum radiances.

% for the left cube and 0.73 RMSE% for the right cube, indicating good long-term repeatability. The short-term repeatability within 24 h of 0.40 RMSE% (left cube) and 0.42 RMSE% (right cube). Additionally, the RMSE percent error was used to measure the consistency between the left and right cubes, with an average value of 2.21%. These test results demonstrated that the device is stable and reliable, with good consistency between the left and right cubes. Note, however, that the since the SPDs was monitored frequently during the experiments, any variability, however small, was controlled.

We analyzed the effects of individual differences on the color matches by applying the CIEPO06 model based on Stockman and Sharpe[15–18] and extended by Stockman and Rider.[19] This model allows us to easily generate cone spectral sensitivities with different macular and lens pigment optical densities, different cone photopigment spectral shifts and different photopigment optical densities. The CIEPO06 L-cone fundamental was not used for this analysis because it is an average of the L(ser180) and L(ala180) cone fundamentals in the ratio of 0.56:0.44 (see for details Ref. 16,19). Instead, we used the L(ser180) cone fundamental from that paper, the continuous formula for which is given in Table 4 of Stockman and Rider.[2] In this type of analysis, single rather than mixed photopigment spectra are required.

We used Maxwell's method to measure color matches (see Figure 1). A standard white combination of the 640, 530, and 445 nm lights adjusted so that the white had a correlated color temperature (CCT) of 7500 K and a luminance of 120 cd/m^2 was presented in the standard half-field. Those LEDs were chosen because their center wavelengths closely correspond to the monochromatic lights used by Stiles and Burch (645, 526, and 444 nm). They were also the "primary" lights used in mixture field.

TABLE 1 The system performance.

Center wavelength (nm)	FWHM (nm)	Shift (nm)	Peak luminance (cd/m^2)	Short-term repeatability (RMSE%) Left cube	Short-term repeatability (RMSE%) Right cube	Long-term repeatability (RMSE%) Left cube	Long-term repeatability (RMSE%) Right cube	Disagreement (%)
430	17	1	11.22	0.05	0.11	0.54	0.72	0.24
445	16	3	16.96	0.50	0.37	0.09	0.79	1.44
460	19	4	27.87	0.09	0.24	0.59	1.08	1.51
475	30	8	58.91	0.62	0.34	0.69	0.67	2.90
505	31	5	125.50	0.09	0.32	0.40	1.04	1.64
530	35	7	160.50	0.11	0.28	0.73	0.42	1.20
545	39	10	326.90	0.72	0.47	0.55	0.63	0.55
560	37	1	113.40	0.41	0.27	0.47	0.74	3.31
595	14	4	128.70	0.05	0.17	0.49	0.33	0.16
605	15	3	117.00	0.54	0.60	0.56	0.51	0.04
640	20	5	63.77	0.63	0.37	0.34	0.73	1.39
660	16	2	56.40	0.03	0.13	0.50	0.97	0.40
675	22	3	23.01	0.49	0.57	0.73	0.91	5.98

TABLE 2 The 11 different primary triplets used in the mixture half-field (primaries in bold).

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

The first triplet in Table 2 is the made up of the three primaries. For the remaining matches, the mixture half-field on the left was illuminated by one of the 10 triplets of LEDs listed in Table 2, which were made up of two of the primary lights and one of the 10 test lights. The model we fit to our data (see Section 3.2 below) has seven parameters per FOV (and 11 parameters in total, as three are shared across FOV—lens density, and L- and M-cone spectral shifts), necessitating several independent color matches. We used 11 color matches to improve the robustness of the fits and to account for any potential redundancy in the sets of triplets we used, while keeping the experimental time as short as possible.

We followed the convention of replacing one of the primaries with the variable-wavelength test light, but we recognize that it might be more efficient to change the wavelengths of more than one or all of the three lights in the matching field.

Figure 4 shows the 11 sets of primaries plotted in the CIE 1976 *u'v'* chromaticity diagram.[30] The CIE 1976 *u'v'* diagram provides a more uniform distribution of perceivable colors, which means that the perceived difference between colors is more consistent across the diagram. This makes it better for certain applications like color difference calculations. The boundary of the graph represents colors of pure wavelengths—the spectral or monochromatic colors. This color space is commonly used to measure the color gamut size of displays. Considering that the 11 triplets in this paper can be regarded as 11 different displays, we can also use this color space to measure the color gamut size that each set of primaries can cover, shown as colored triangles.

2.3 | Observers

Five male observers participated in this experiment with ages of 22, 25, 21, 22, and 24 years for Observers 1–5, respectively. Observers have a mean age of 23. All five

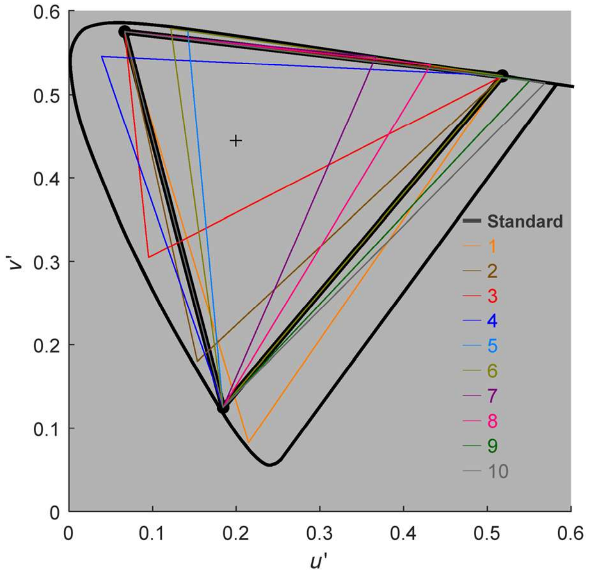

FIGURE 4 Color gamut of the 11 triplets on CIE 1976 *u'v'* chromaticity diagram with '+' as the white standard.

observers successfully passed the Ishihara color vision test. They repeated the color matches in the experiment five times, and their matches confirmed that they are color normal (see below).

2.4 | Procedures

Observers were presented with a white standard in the right half-field and were asked to match it by adjusting the intensities of the triplet of matching lights illuminating the mixture half-field on the left. A simultaneous binocular matching technique is used. Observers see both fields at the same time using both eyes. The triplets are listed in Table 2. In general, we used the same three primary lights that illuminated the right reference white half-field (640, 530, and 445 nm) but replaced one of them with a light of different wavelength such that the new triplet enclosed the white standard (see Figure 4). The observer was asked to match the reference white by directly adjusting the intensity of the three matching lights with control knobs. A simultaneous binocular matching technique was used to perform color matching. Observers observed both fields at the same time using both eyes.

The experiment was conducted in a dark room, with a chin rest used to fix the observer's position at 50 cm from the fields. Observers received initial training lasting approximately 15–30 min before making color matches. At the start of the experiment, observers were adapted to the testing environment for 2 min before making color matches with a field of view (FOV) of 10° visual angle until the 11 matches were completed. Observers were instructed to ignore, if visible, any color difference in the center of the field (i.e., Maxwell's spot, due to the higher macular pigment density in central retina) and to make the match according to the color seen in the outer region of the fields. After a brief rest and readaptation, the observers completed a further 11 color matches with a 2° FOV. The five observers completed the experiment five times, resulting in a total of 110 matches (11 triplets × 2 FOVs × 5 repeats) for each observer. On average, it took 70 min to complete one set of matches. Thus, the experiment lasted about 350 min for each observer.

3 | RESULTS

3.1 | Color matching variability

The spectral power distributions (SPDs) of the mixed triplets of lights that the observers matched to the white standard were measured after each experimental run with the spectroradiometer placed at the observer's pupil position. For each SPD, we calculate the XYZ tristimulus values by cross-multiplying and summing over wavelength,

$$\begin{bmatrix} X_w \\ Y_w \\ Z_w \end{bmatrix} = \int_{380}^{780} \mathrm{CMF}(\lambda)\mathrm{SPD}_w(\lambda)d\lambda, \quad (1)$$

$$\begin{bmatrix} X_m \\ Y_m \\ Z_m \end{bmatrix} = \int_{380}^{780} \mathrm{CMF}(\lambda)\mathrm{SPD}_m(\lambda)d\lambda, \quad (2)$$

where $[X_w\ Y_w\ Z_w]^T$ and $[X_m\ Y_m\ Z_m]^T$ are the tristimulus values of the white reference stimuli and matched color made by observers; CMF is the CIE standard CMF, that is, CIE 2006 2° CMF; SPD_w and SPD_m are the SPDs of reference stimuli and matched color. We then calculate the color difference by applying the CIEDE2000 color difference formula,[24] to estimate the matching errors for specific observer or triplet.

These differences provide an estimate of the between or interobserver variability, and, since each observer carried out five separate matches, also of the within observer or intraobserver variability. The intraobserver and interobserver variations were quantified using the mean color differences from the mean (MCDM). Since five matches for each triplet were done by observers, the mean color difference between these five matches showed

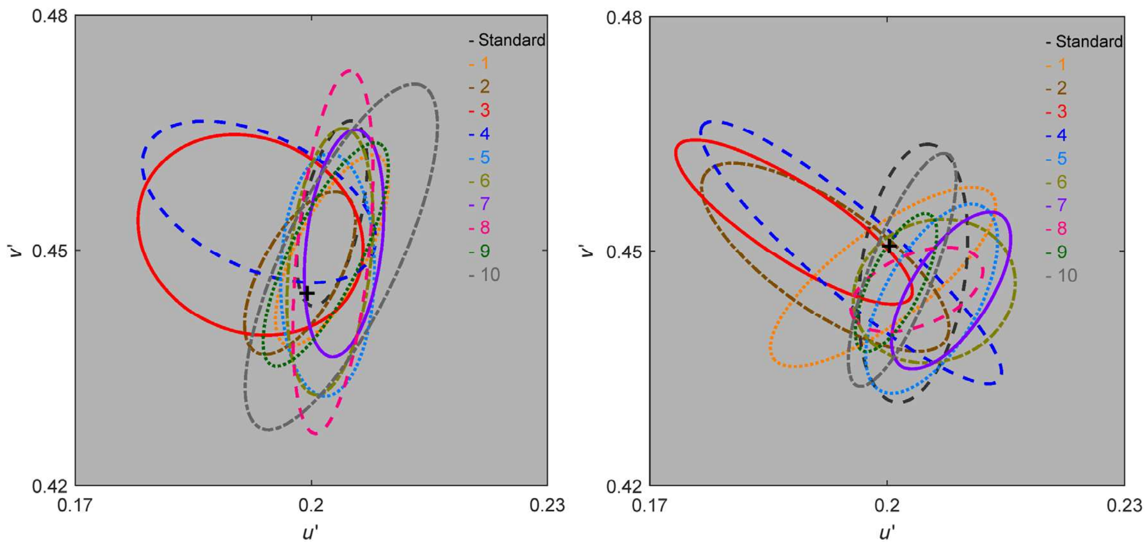

FIGURE 5 The 95% confidence ellipses for each triplet (left: 2°, right: 10°, '+': reference).

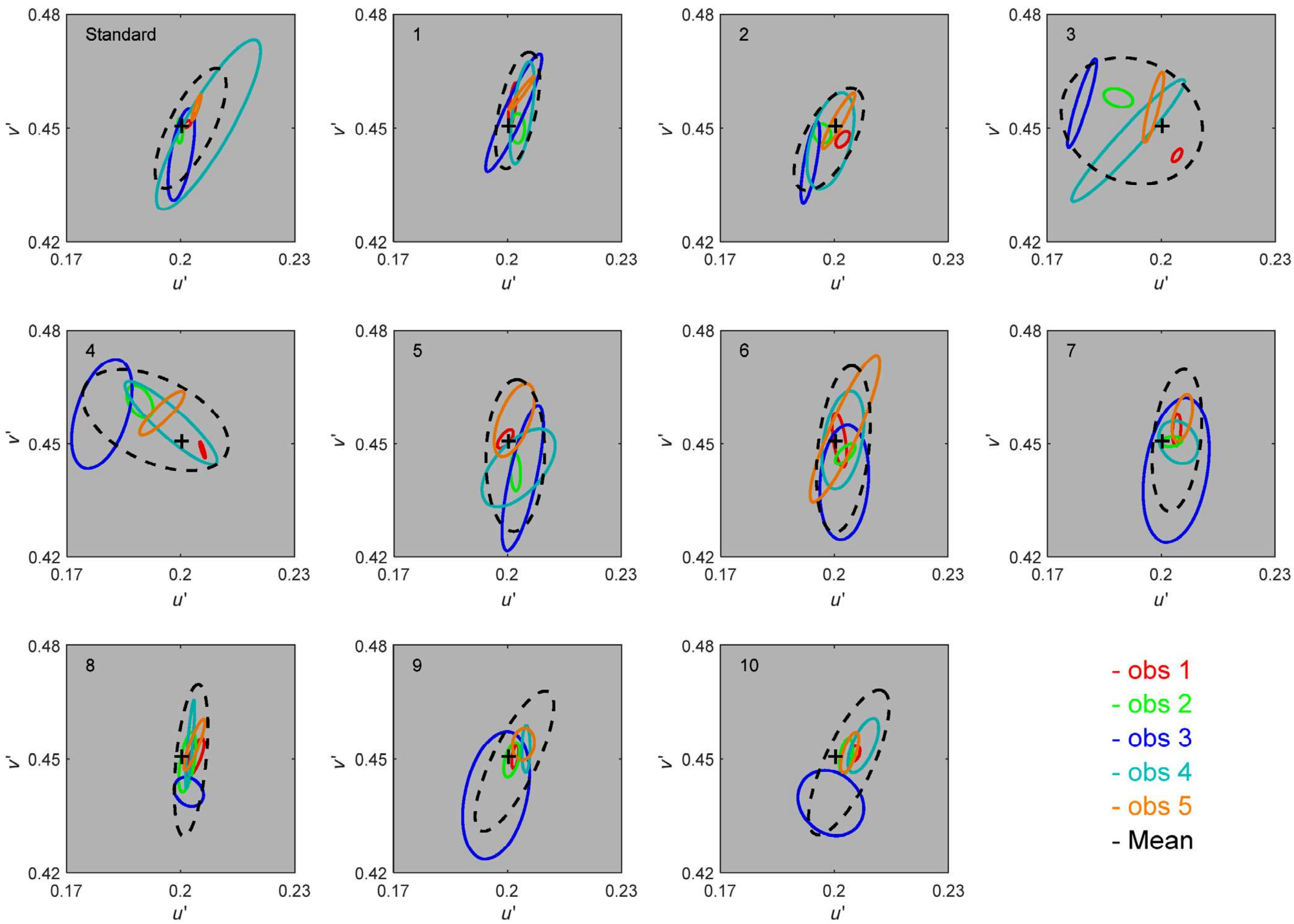

FIGURE 6 The 95% confidence ellipses from each observer in 2° experiment. Each panel shows a different mixture triplet.

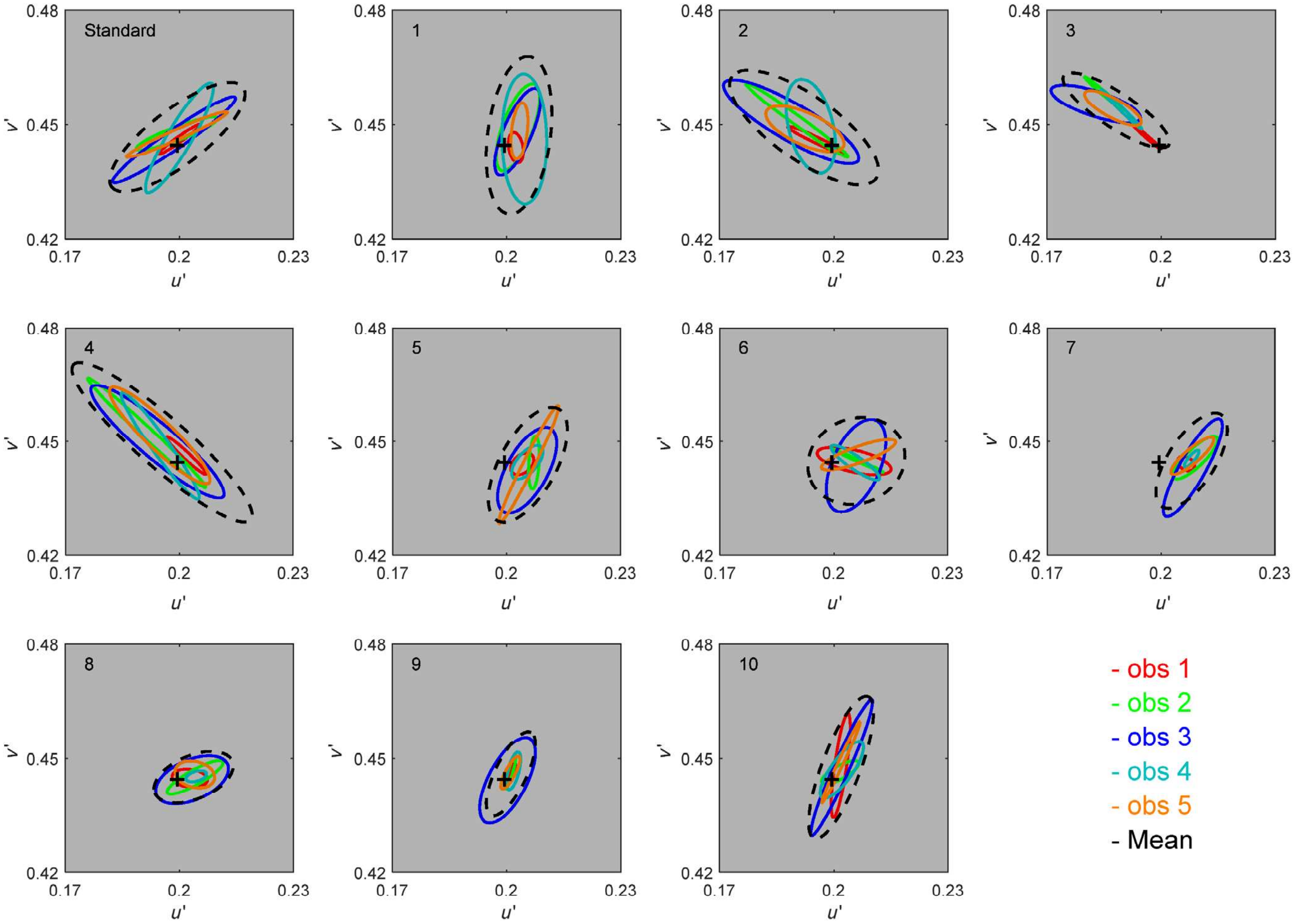

FIGURE 7 The 95% confidence ellipses from each observer in 10° experiment. Each panel shows a different mixture triplet.

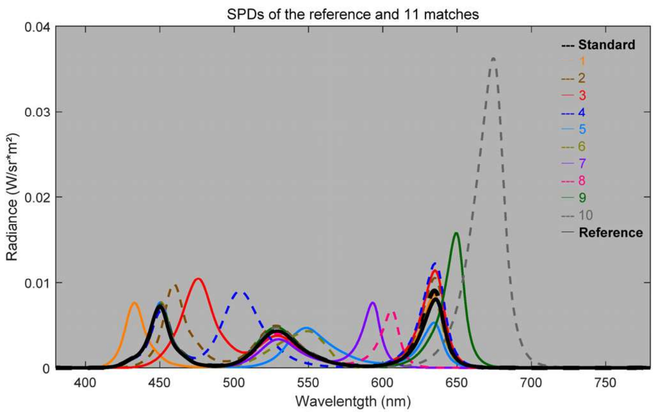

FIGURE 8 The averaged 12 matched white spectra in 2°experiments across 5 observers (the reference and 11 matches). Note, the Reference spectrum (solid black curve) is the one presented in the right field to which all matches were made, and the Standard spectrum (dashed black curve) is the match made using the same set of LEDs in the left matching field.

intraobserver variation. Similarly, the color difference between matched colors in specific triplets made by different observers shows the difference across individuals, that is, the interobserver variability.

For interobserver variation, the MCDM values for 2° and 10° experiment were 4.62 and 4.16 ΔE_{00} units, respectively. Figure 5 shows the 95% confidence ellipses of the two experiments from five observers. The 11 ellipses represent the 11 triplets used in the experiment, with each ellipse fitted to 25 data points (5 repeats from the 5 observers).

Within observers, we found mean MCDM values of 2.91 ΔE_{00} units for the 2° experiment, and 2.32 ΔE_{00} units for the 10° experiment. The differences between observers can be represented by fitting 95% confidence ellipses to their mean data. Figures 6 and 7 shows the individual 95% confidence ellipses from five observers representing the intraobserver variations, while the ΔE_{00} units were 1.29, 1.78, 4.62, 3.85, 2.06 individually for five observers in 2° experiment, and 1.51, 1.96, 3.32, 2.95, 1.82 for 10° experiment. Overall, the observers showed good intraobserver differences, but the values for the third and fourth observers were slightly higher, indicating that their stability was slightly worse.

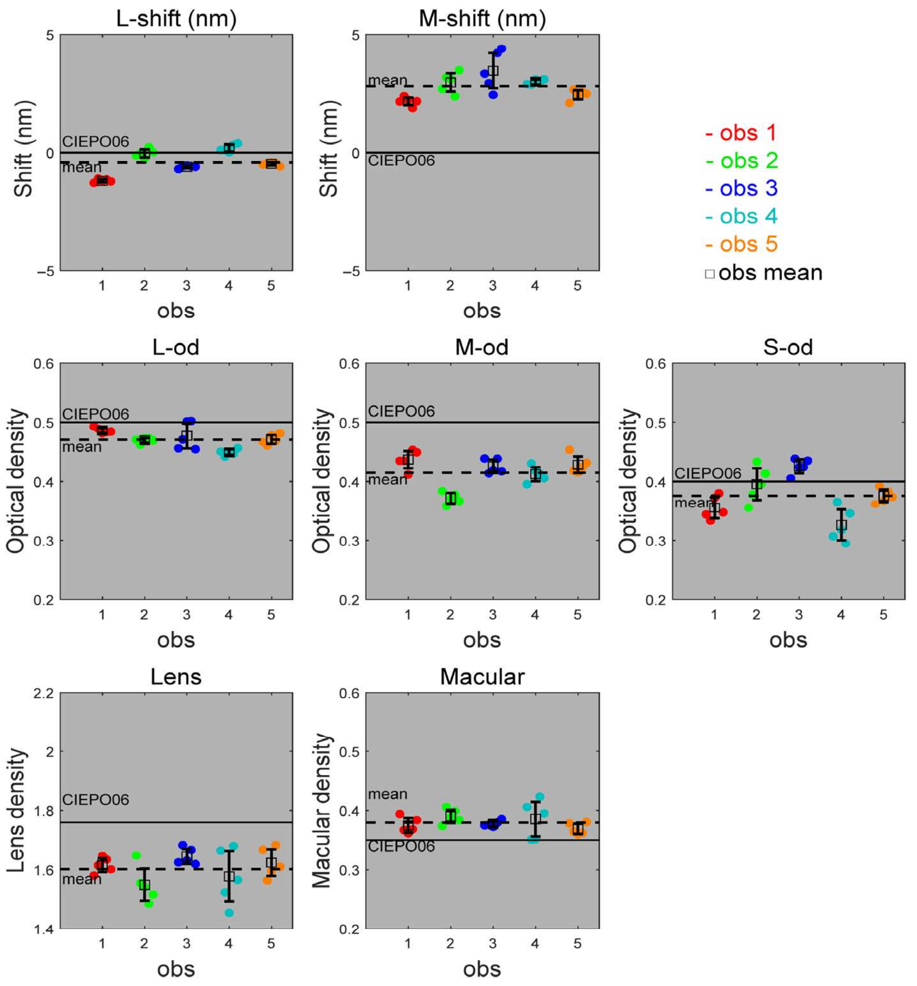

FIGURE 9 The distributions of seven parameters for each observer for 2° cone fundamentals.

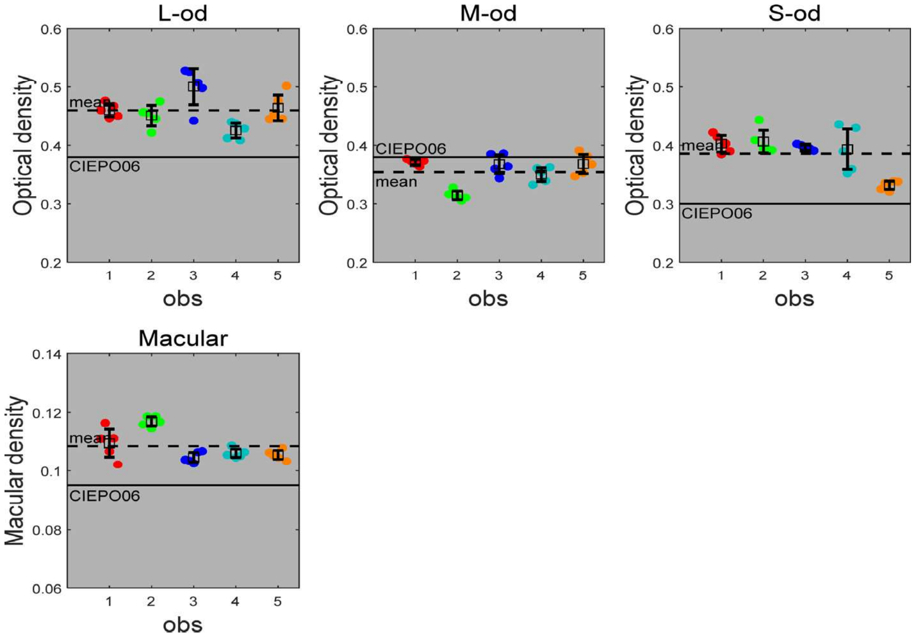

FIGURE 10 The distributions of four parameters for each observer for 10° cone fundamentals.

As well as comparing the variability within and between our observers, we also compared the difference between our observers and the prediction of the CIEPO06 standard observer. The average matching error (the average of the individual averages) for 2° matches was 7.72 ΔE_{00} units, and 5.09 ΔE_{00} units for the 10° experiment.

TABLE 3 Mean and standard errors of model parameters fitted to the 2° matches for each observer, and the absolute values for these as given in the original Stockman & Sharpe work.

Observers	L_{shift}	M_{shift}	l_{OD}	m_{OD}	s_{OD}	lens (at 400 nm)	macular (at 460 nm)
Obs 1	−1.20 ± 0.20	2.10 ± 0.20	0.49 ± 0.03	0.43 ± 0.02	0.36 ± 0.04	1.63 ± 0.07	0.370 ± 0.021
Obs 2	0.20 ± 0.40	2.90 ± 0.70	0.47 ± 0.01	0.36 ± 0.02	0.38 ± 0.05	1.53 ± 0.09	0.384 ± 0.032
Obs 3	−0.60 ± 0.10	3.50 ± 0.80	0.49 ± 0.04	0.42 ± 0.04	0.42 ± 0.02	1.63 ± 0.14	0.379 ± 0.014
Obs 4	0.20 ± 0.30	3.30 ± 0.50	0.45 ± 0.01	0.41 ± 0.02	0.35 ± 0.06	1.60 ± 0.11	0.373 ± 0.035
Obs 5	−0.50 ± 0.10	2.50 ± 0.60	0.47 ± 0.03	0.43 ± 0.02	0.35 ± 0.05	1.64 ± 0.11	0.381 ± 0.028
Original	0	0	0.50	0.50	0.40	1.76	0.350

TABLE 4 Mean and standard errors of model parameters fitted to the 10° matches for each observer, and the absolute values for these as given in the original Stockman & Sharpe work.

Observers	L_{shift}	M_{shift}	l_{OD}	m_{OD}	s_{OD}	lens (at 400 nm)	macular (at 460 nm)
Obs 1	−1.20 ± 0.20	2.10 ± 0.20	0.46 ± 0.02	0.37 ± 0.03	0.40 ± 0.03	1.63 ± 0.07	0.107 ± 0.008
Obs 2	0.20 ± 0.40	2.90 ± 0.70	0.43 ± 0.04	0.31 ± 0.03	0.41 ± 0.03	1.53 ± 0.09	0.116 ± 0.005
Obs 3	−0.60 ± 0.10	3.50 ± 0.80	0.47 ± 0.04	0.36 ± 0.04	0.40 ± 0.02	1.63 ± 0.14	0.107 ± 0.004
Obs 4	0.20 ± 0.30	3.30 ± 0.50	0.43 ± 0.03	0.35 ± 0.04	0.39 ± 0.04	1.60 ± 0.11	0.105 ± 0.003
Obs 5	−0.50 ± 0.10	2.50 ± 0.60	0.47 ± 0.03	0.37 ± 0.05	0.33 ± 0.01	1.64 ± 0.11	0.106 ± 0.002
Original	0	0	0.38	0.38	0.30	1.76	0.095

Comparing these values to the interobserver variability given above, we see that our observers were on average more similar to each other than to the standard observer. In general, the matching errors for the 10° matches were less than for the 2° matches.

3.2 | Deriving cone spectral sensitivities

As noted above, the matches can be used to derive the individual cone spectral sensitivities for each of the five observers. This is because all the matched whites for a given observer should produce the same three cone excitations for that observer. Consequently, when the SPDs for the matched whites set by an observer are cross-multiplied with each of his or her three cone spectral sensitivities and summed, all the S-cone values should be the same, all the M-cone values should be the same and all the L-cone values should be the same. Our goal in analyzing the color matching data of an observer was to derive the three cone spectral sensitivities for that observer for which the three values are similar. This was achieved by applying the extended CIEPO06[13] model developed by Stockman and Rider,[19] in which the L-, M-, and S- cone absorbance spectra and for the standard lens and macular optical density spectra are defined as continuous functions of wavelength, and optimizing the optical densities of the L-, M-, and S-cones (i.e., l_{OD}, m_{OD}, and s_{OD}), the lens and macular densities (k_{lens} and k_{mac}), and the spectral shifts of the L and M cones (L_{shift} and M_{shift}) to minimize the squared differences in the L, M, and S-cone excitations across the 12 matched white spectra (the reference and 11 matches). In calculation process, the 12 matched white spectra (see Figure 8) are cross-multiplied by the L-, M-, and S- cone fundamental function to derive the cone excitations. In the fitting process for each observer, the 7 parameters were chosen to minimize the squared differences in the L, M, and S-cone excitations across the 12 matched white spectra.

The model was fitted simultaneously to all the 2° and 10° matched white SPDs. The model was fitted simultaneously to all the 2° and 10° matched white SPDs, and it was assumed that three parameters were constant across FOV (L_{shift}, M_{shift}, and k_{lens}). The others varied with FOV.

Figures 9 and 10 show the best-fitting parameter values for each run (circles) and the mean and (squares) one standard error across the five runs for each observer. The mean parameter across observers is shown by the dashed line in each panel. Tables 3 and 4 list the best-fitting 2° and 10° parameters, respectively. Figure 10 does not show the L_{shift}, M_{shift}, and k_{lens} data since they are identical to Figure 9, that is, they are constant across FOV.

As expected for color normal observers, all the best-fitting parameters are relatively close to the parameters assumed in the CIEPO06 model but show some interesting differences. In this population of young Chinese observers, the L-cones are shifted about 2 nm to shorter wavelength and the M-cones about 3 nm to longer wavelength. Furthermore, the l_{OD} and m_{OD} values were slightly lower for the 2° FOV than for CIEPO06. More unexpectedly, the s_{OD} was higher for the 10° FOV than for 2°, since outer segment length and thus optical density is usually assumed to decrease the eccentricity.[17]

The fits of the CIEPO06 model are broadly consistent with the CIE standard observer. The relatively minor differences we find might be due to individual differences between the two populations in which the measurements were made, errors in the CIEPO06 model, or biases introduced by our model fits and/or problems with our instrumentation. We are pursuing these questions by enlarging

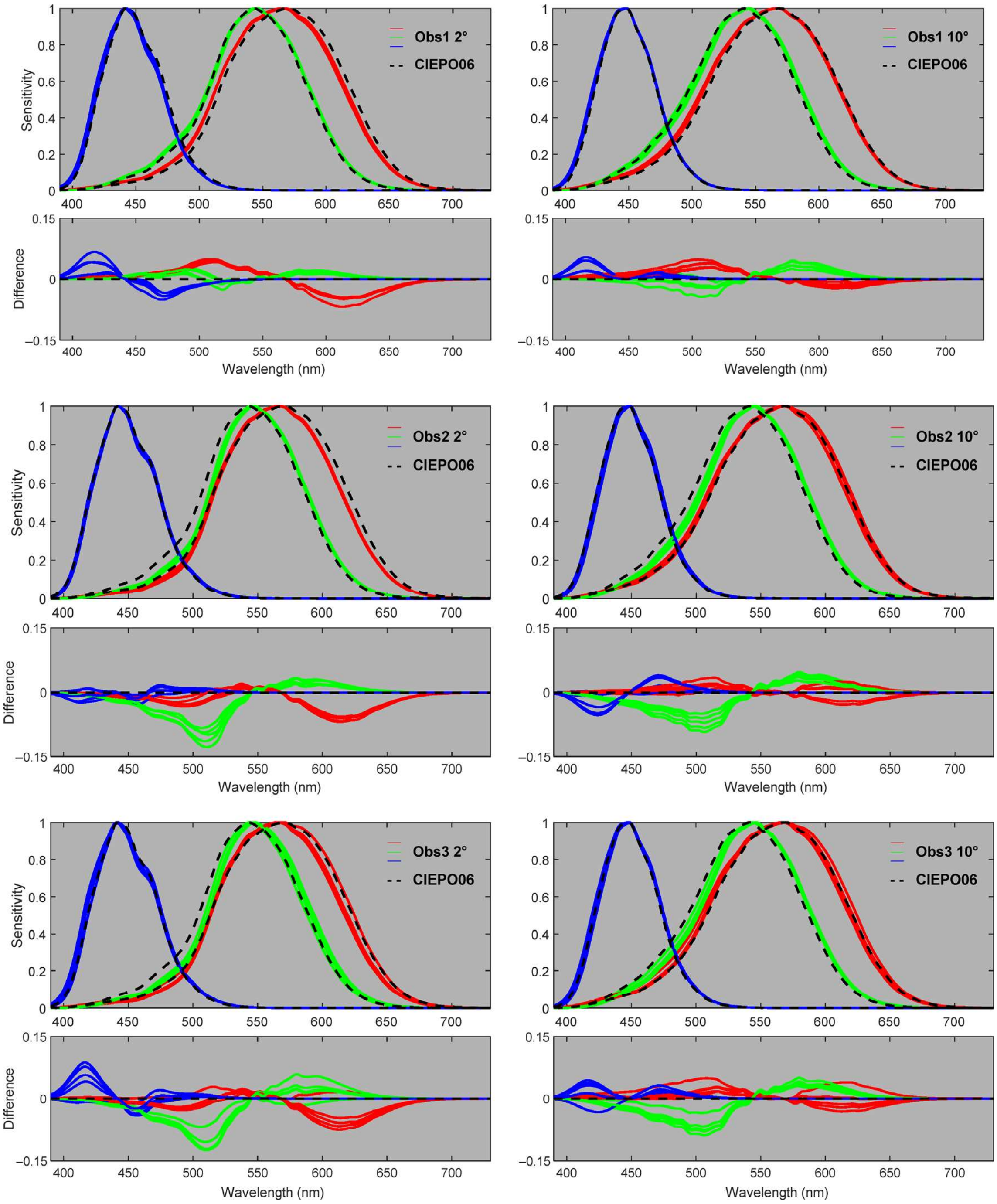

FIGURE 11 The cone fundamentals corresponding to all sets of parameters.

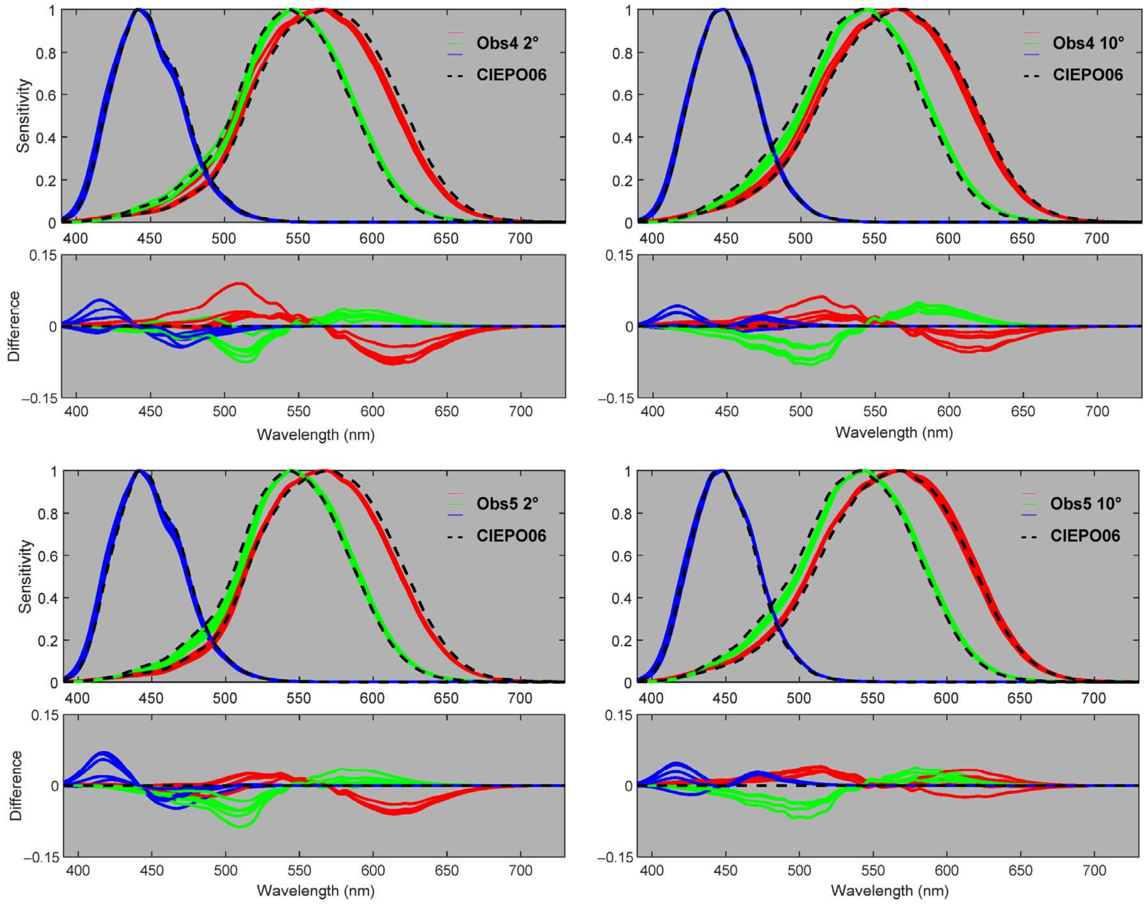

FIGURE 11 (Continued)

our population database to include other observers of different ages, ethnicities, and of both sexes. In the table, the macular in all cases is defined as the peak density at 460 nm. Thus, it is 0.35 for 2 deg and 0.095 at 10-deg at 460 nm. The lens original in 1.76 is the density at 400 nm as in work of Stockman and Sharpe.[14]

The larger panels of Figure 11 show the five estimates of the L-, M-, and S-cone fundamentals (solid red, green, and blue lines, respectively) for each observer and for each FOV. The CIEPO06 cone fundamentals are shown by the black dashed lines. The smaller panels show the differences between the estimates and CIEPO06 fundamentals. The most prominent differences seen in the red and green curves are due to the spectral shifts described above.

4 | CONCLUSION

Color matches are the cornerstone of color specification and color science, and directly reflect the underlying L-, M-, and S-cone spectral sensitivities. Comparing color matches across observers is a useful means of quantifying individual differences in the corneal cone spectral sensitivities across observers. A multi-primary visual trichromator illuminated by LED light sources was initially designed and built for this project, and with it a series of color matches were made by five color normal observers. The system calibrations were stable and the within observer variability small, which confirm the reliability of the experimental data.

Comparing with the standard observer model, CIEPO06, based on Stiles and Burch's canonical CMFs, we found that the results are broadly consistent, as expected for relatively young color normal observers, but they deviate in small and systematic ways. In order to represent the average or typical color normal observer, the standard observer model fixes the optical densities of the lens, macular and cone photopigments (all of which can vary significantly in the general population), and the spectral positions of the L- and M-cone absorbance spectra, which also vary due to polymorphisms in the opsin genes. We applied a model for estimating individual cone spectral sensitivities to the color matching data and found that small but consistent changes to the standard observer model can better predict individual's data. The

CMFs that can be derived from these fits are plausible estimates of the individual's true underlying CMFs.

A highly consistent finding in our model fits is that all five observers show small shifts of the M-cone spectra to slightly longer wavelengths, which could be a result of polymorphisms, but perhaps is more likely due the difficulty of independently estimating the M-cone spectral shift as this may be confounded with estimates of the optical densities of the M-cones as well as of the lens and macular. Unfortunately, our observers have not been genotyped which would help to confirm or refute this hypothesis.

We are currently measuring Maxwell color matches in a population of observers with mild, moderate and severe color vision deficiency. The larger expected spectral shifts of the L- and M-cones in this population will provide a more stringent test of both the trichromator, where poorer color discrimination will likely increase the variability in the individual's color matches, and of the general applicability of the model.

AUTHOR CONTRIBUTIONS

Keyu Shi: Experimental design; data collection; analysis and writing. **Ming Ronnier Luo**: Manuscript revision. **Andrew T. Rider**: Data analysis; manuscript revision. **Tingwei Huang**: Technical support. **Lihao Xu**: Data analysis. **Andrew Stockman**: Experimental design; data analysis; manuscript revision.

ACKNOWLEDGMENTS

We thank the anonymous reviewers whose comments/suggestions helped to improved the clarity of the manuscript, and thank Siyuan Song for his help with the experiments and algorithms.

FUNDING INFORMATION

National Natural Science Foundation of China (61775190 and 62305096) and the BBSRC, UK (BB/R019487/1).

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

Keyu Shi https://orcid.org/0009-0000-4389-1059
Ming Ronnier Luo https://orcid.org/0000-0003-1014-0034
Andrew T. Rider https://orcid.org/0000-0001-8251-1100
Lihao Xu https://orcid.org/0009-0001-4473-2065
Andrew Stockman https://orcid.org/0000-0001-9807-6289

REFERENCES

[1] A. Stockman and L. T. Sharpe, "Cone spectral sensitivities and color matching," in K. Gegenfurtner & L. T. Sharpe (Eds.), *Color Vision: From Genes to Perception* (PP. 53–87) Cambridge University Press, 1999), pp. 53–87.
[2] Webster M, MacLeod RD. Factors underlying individual differences in the color matches of normal observers. *J Opt Soc Am A*. 1988;5:1722-1735.
[3] Stiles WS, Burch JM. NPL colour-matching investigation: final report. *Opt Acta*. 1959;6:1-26.
[4] Asano Y, Fairchild MD, Blondé L. Individual colorimetric observer model. *PLoS One*. 2016;11:e0145671.
[5] Asano Y, Fairchild MD, Blondé L, Morvan P. Color matching experiment for highlighting interobserver variability. *Color Res Appl*. 2016;41:530-539.
[6] Guild J. The colorimetric properties of the spectrum. *Philos Trans R Soc A*. 1931;230:149-187.
[7] Wright WD. A re-determination of the trichromatic coefficients of the spectral colours. *Trans Opt Soc*. 1929;30:141-164.
[8] Wright WD. A re-determination of the mixture curves of the spectrum. *Trans Opt Soc*. 1930;31(4):201-218.
[9] Commission Internationale de l'Eclairage. CIE Proceedings. Vienna Session, 1963, Vol. B (Committee Report E-1.4.1). 1963.
[10] Speranskaya NI. Determination of spectral colour co-ordinates for twenty-seven normal observers. *Opt Spectrosc*. 1959;7:424-428.
[11] Wyszecki G, Stiles WS. *Color Science: Concepts and Methods, Quantitative Data and Formulae*. 2nd ed. John Wiley Sons; 2000.
[12] Wu J, Wei M, Fu Y, Cui C. Color mismatch and observer metamerism between conventional liquid crystal displays and organic light emitting diode displays. *Opt Express*. 2021;29:12292-12306.
[13] Shi K, Luo MR. Factors affecting colour matching between displays. *Opt Express*. 2022;30:26841-26855.
[14] Ko M, Kwak Y, Seo G, Kim J, Moon Y. Reducing the CIE colorimetric matching failure on wide color gamut displays. *Opt Express*. 2023;31:5670-5686.
[15] Stockman A, Sharpe LT, Fach C. The spectral sensitivity of the human short-wavelength sensitive cones derived from thresholds and color matches. *Vision Res*. 1999;39:2901-2927.
[16] Stockman A, Sharpe LT. The spectral sensitivities of the middle- and long-wavelength-sensitive cones derived from measurements in observers of known genotype. *Vision Res*. 2000;40:1711-1737.
[17] Commission Internationale de l'Eclairage. Fundamental chromaticity diagram with physiological axes—part 1, Vol CIE 170–1. Central Bureau of the Commission Internationale de l' Eclairage; 2006.
[18] Commission Internationale de l'Eclairage. Fundamental chromaticity diagram with physiological axes—part 2: spectral luminous efficiency functions and chromaticity diagrams, Vol CIE 170–2. Central Bureau of the Commission Internationale de l' Eclairage; 2015.
[19] Stockman A, Rider A. Formulae for generating standard and individual human cone spectral sensitivities. *Color Res Appl*. 2023;48:818-840.

[20] Oicherman B. *Effects of Colorimetric Additivity Failure and of Observer Metamerism on Cross-Media Colour Matching*. Department of Colour Science, University of Leeds, PhD; 2007.
[21] Morvan P, Sarkar A, Stauder J, Blondé L, Kervec J. A handy calibrator for color vision of a human observer. *2011 IEEE International Conference on Multimedia and Expo*. IEEE; 2011: 1-4.
[22] Sarkar A. *Identification and Assignment of Colorimetric Observer Categories and their Applications in Color and Vision Sciences*. Signal Image Process, Université de Nantes, PhD; 2011.
[23] Asano Y. *Individual Colorimetric Observers for Personalized Color Imaging*. Munsell Color Science Laboratory, Rochester Institute of Technology, PhD; 2015.
[24] Asano Y. Multiple color matches to estimate human color vision sensitivities. *International Conference on Image and Signal Processing*. Springer International Publishing; 2014.
[25] Maxwell JC. On the theory of compound colours and the relations of the colours of the spectrum. *Philos Trans R Soc London*. 1860;150:57-84.
[26] Grassman H. On the theory of compound colours. *London Edinburgh Philos Mag J Sci*. 1854;7:254-264.
[27] Crawford BH. Color matching and adaptation. *Vision Res*. 1965;5:71-78.
[28] Zaidi Q. Adaptation and color matching. *Vision Res*. 1986;26: 1925-1938.
[29] Guild J. A trichromatic colorimeter suitable for standardisation work. *Trans Opt Soc*. 1925;27:106-129.
[30] CIE. *Colorimetry. Publication CIE No. 15.2*. 2nd ed. Commission Internationale de l'Eclairage; 1986.

AUTHOR BIOGRAPHIES

Keyu Shi is a PhD student at the College of Optical Science and Engineering, Zhejiang University (China), focusing on color science. He received his BSc degree in Electronic Information School from Wuhan University (China) in 2019. His research areas include the development and validation of color appearance models; the investigation of observer metamerism and color correction models; and individual difference in cone fundamentals and color matching functions.

Ming Ronnier Luo is a Qiushi Professor at the College of Optical Science and Engineering, Zhejiang University (China). He is a Senior Editor of Color Research and Application. He received his PhD from the Bradford University (UK) in color science in 1986. He has published over 750 peer reviewed papers in the fields of color science, imaging science and illumination engineering. He is a Fellow of the Society of Dyers and Colourists (SDC) and of Imaging Science and Technology (SIST). He has been an active member of International Commission on Illumination (CIE), including Vice President, Division Director on Color and Vision, and has chaired several Technical committees. He has received numerous awards, including the Judd 2017 Award from the International Color Association (AIC), and the Newton 2020 medal from the Color Group of the Great Britain for his contributions to color science research.

Andrew T. Rider is a postdoctoral research associate at University College London Institute of Ophthalmology. He has a PhD in cognitive neuroscience from UCL, a masters degrees in biological modeling (UCL) and medical statistics (London School of Hygiene and Tropical Medicine), and a BA in mathematical sciences (University of Oxford). His research uses mathematical modeling and psychophysical measurements to study human vision. His work includes models of cone temporal sensitivity and light adaptation; nonlinear models of color processing and measurements of visible distortion that allow the visual system to be dissected into early and late stages; and models of interactions between fast and slow signals in visual processing.

Tingwei Huang is a technical director at Thousand Lights Lighting (Changzhou) Limited. He received his PhD from the Department of Optics and Photonics in the National Central University (TW) in 2011. He has published over 60 papers and granted over 40 patents in the fields of color engineering, illumination engineering, optical design, encoder, and biomedical application of spectrum.

Lihao Xu received his BE and PhD degrees from the Department of Optical Engineering of Zhejiang University, China, in 2013 and 2018 respectively. He is currently a lecturer with School of Digital Media and Art Design, Hangzhou Dianzi University, China. His research interests include color science, imaging science, and illumination engineering.

Andrew Stockman is the Steers Chair of Investigative Eye Research at University College London Institute of Ophthalmology and part-time Professor of the College of Optical Science and Engineering, Zhejiang University. He is the Editor-in-Chief of Color Research and Application. He is a leading vision researcher, who specializes in color vision, rod vision, visual adaptation, temporal sensitivity, retinal processing, and clinical vision. He is well known for the "Stockman & Sharpe" cone spectral sensitivities, which have been adopted by the CIE as international standards for color definition and color measurement, and which are the subject of this paper. Other important work includes measurements and models of cone and rod temporal sensitivity and delay that have led to the identification of slow and fast signals in photopic, mesopic and scotopic vision, including the discovery of an unexpected slow, inverted S-cone signal that contributes to luminance; measurements of visible distortion that allow the performance of the visual system to be dissected into early and late stages, measurements and models of light adaptation; and a substantial body of clinical work on understanding and modeling the effects of molecular loss in eye disease.

How to cite this article: Shi K, Luo MR, Rider AT, Huang T, Xu L, Stockman A. A multi-primary trichromator to derive individual color matching functions and cone spectral sensitivities. *Color Res Appl*. 2024;1-16. doi:10.1002/col.22928