Reproducing Color for Human Observers: The Challenges of Individual Differences and How to Compensate for Them

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Abstract

Human color vision depends on the long- middle- and short-wavelength sensitive cone sensors, the spectral sensitivities of which vary across the population. We estimated the variability across 100 observers from a series of color matches using a newly developed trichromator that we call LEDMax. The individual cone spectral sensitivity functions that result can be used to optimize the colours produced by display devices.

Author Keywords

Colour vision; cone spectral sensitivities; individual differences; color matching functions; color reproduction; color appearance.

1. Introduction

Human color vision depends on the spectral sensitivities of the three daytime photoreceptors: the short-wavelength (S-), middle-wavelength (M-) and long-wavelength (L-) sensitive cones. This paper brings together a series of experiments that have used a newly developed trichromator called LEDMax to infer the cone spectral sensitivities of individual observers and thus also estimate the individual differences between them. The method relies on asking observers to adjust many triplets of lights of different wavelengths to match the same white standard light. Given that for a single observer the matched triplets should all produce identical L-, M- and S-cone excitations, we can use the matches to estimate the LMS cone spectral sensitivities that best fulfill this condition for that observer. The cone spectral sensitivities were found by optimizing the cone spectral sensitivities generated by the CIEPO06 model published by the CIE in 2006 (1) (and based almost entirely on work by Stockman, Sharpe & Fach (2) and Stockman & Sharpe (3)), and more recently extended by Stockman & Rider (4). This extended model allows the known factors that cause individual differences in spectral sensitivity to be varied to best account for the matches. These known factors are the densities of macular and lens pigments (which lie between the cornea and the cones), the optical densities of the pigments within the cones, and spectral shifts of the L- and M-cone photopigment (see, for review, 5).

This review brings together work from three papers (6-8) and will include new data from color deficient observers. The color matches are made using a multi-LED visual trichromator, the details of which can be found in our previous paper (6). Briefly, two multi-LED light sources separately illuminated two uniform, vertically abutting semi-circular half-fields (see Figure 1), and the intensities of the LEDs making up each light source could be independently varied. Apertures were used to restrict the size of the resulting circular field to 2° or 10° fields of view (FOV).

Measurements have been made in over 100 observers varying in age from 8 to 79 years of age (6-8), the results of which will be described below. We have also made measurements in several color deficient observers.

This work responds to the need not only for better standard or mean LMS cone spectral sensitivities and the related XYZ CMFs but also for more reliable estimates of the effects of individual variability. This need has become more pressing with advancements in display technologies and the introduction of narrowband primary lights that expand the color gamut (e.g., LCD, OLED, Mini-LED, QD-OLED and laser devices). Such narrowband lights typically accentuate the effects that individual differences in spectral sensitivities can have on color reproduction. Moreover, these difficulties are exacerbated by the continued use of the widely used, yet fundamentally flawed, CIE 1931 color matching functions, which fail to accurately reproduce colors even for the mean normal observer especially at shorter wavelengths (9-13).

2. Methods

We developed a multi-LED visual trichromator for the color matching experiments. The right-hand half-field was illuminated by three LEDs with center wavelengths of 640, 530, and 445 nm that were together adjusted to produce a fixed standard white with a correlated color temperature (CCT) of 7500K and a luminance of 120 cd/m2. On each trial the left-hand matching half-field was illuminated by one of 11 triplets of LEDs: [640, 530, 445], [640, 530, 430], [640, 530, 460]*, [640, 530, 475]*, [640, 505, 445], [640, 545, 445], [640, 560, 445]*, [595, 530, 445], [605, 530, 445], [660, 530, 445], and [675, 530, 445]*. The starred triplets were matched twice by each observer to assess intra-observer variability.

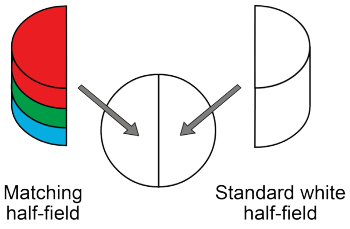

Figure 1. Maxwell's color matching method.

Observers adjusted the triplet of LEDs making up the left matching half-field until they were satisfied that it matched the reference white. To make the adjustments easier for color normal observers, the three LED lights in the matching half-field were transformed using the gain-offset-gamma (GOG) model (14) and polynomial fitting to XYZ tristimulus values, then further converted into the CIELAB space using standard CIE methods. The observer was then asked to vary Lightness, a* (redness-greenness), b* (yellowness-blueness) to match the white standard. Color normal observers found these adjustments to be perceptually more intuitive and easier to perform than adjusting the intensities of the individual LEDs. We call this matching procedure the Lab matching method.

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Table 1. Summary of the means and standard deviations of the best-fitting parameters. The parameter lens gives the density of the lens pigment at 400 nm and mac the optical density of macular pigment at 460 nm.

				2°				10°			
	L_{shift}	M_{shift}	k_{lens}	l_{OD}	m_{OD}	s_{OD}	k_{mac}	l_{OD}	m_{OD}	s_{OD}	k_{mac}
Male	-1.97	2.57	1.82	0.50	0.46	0.39	0.48	0.43	0.37	0.33	0.131
(SD)	(1.31)	(1.56)	(0.39)	(0.10)	(0.07)	(0.11)	(0.16)	(0.08)	(0.08)	(0.08)	(0.024)
Female	-2.01	2.49	1.88	0.50	0.38	0.35	0.53	0.43	0.37	0.35	0.139
(SD)	(1.17)	(1.54)	(0.43)	(0.11)	(0.06)	(0.10)	(0.11)	(0.09)	(0.07)	(0.08)	(0.026)
Mean	-1.97	2.53	1.85	0.50	0.42	0.37	0.51	0.43	0.37	0.34	0.135
(SD)	(1.24)	(1.55)	(0.41)	(0.11)	(0.07)	(0.10)	(0.13)	(0.08)	(0.07)	(0.08)	(0.025)
CIEPO06	0	0	1.76	0.50	0.50	0.40	0.35	0.38	0.38	0.30	0.095

The matching experiment was conducted in a darkened environment to which the observers adapted for 2 minutes prior to the start of the experiment. A chinrest was used to maintain head position 50 cm from the stimulus and the fields were viewed binocularly. All observers underwent a 30-minute training phase before starting the main experiment. During training, they familiarized themselves with the experimental procedures and practiced making color matches. The practice matches were not used in the analysis. In the main experiments, observers first made color matches for a FOV of 10°, until 15 random-order matches were completed (11 matches, one for each triplet list above and four repeats, see below). After a brief rest and re-adaptation, the observer then completed 15 further random-order sets of color matches for a 2° FOV (11 matches, one for each triplet and four repeats). The four triplets that were repeated are starred in the above list. In total, each observer performed 30 color matches, which took on average about 60 minutes. Including adaptation and training time, the total duration of the experiment was approximately 90 minutes. Once the experiment was finished the SPDs of the standard reference and each of the matched lights were measured from the observer's eye position using a Konica-Minolta CS2000 spectroradiometer.

In total, 100 Chinese observers with normal color vision and 22 Chinese observers with a color vision deficiency (anomalous trichromacy) participated in this study. Their ages ranged from 8 to 80 years old. The normal color vision observers initially underwent Ishihara testing to exclude clearly color deficient observers with, of course, the LEDMax matches themselves providing further confirmation that their color vision was normal. The color vision deficient observers were identified and categorized by their results on a variety of standard color vision tests, and of course by their color matches made with the LEDMax.

3. Results

Following the matches, the spectral power distributions (SPDs) of all the test half-fields and the white reference standard were measured using a spectroradiometer placed in the same position as observer's eye and imaged on the fields. These SPDs were used to estimate the individual LMS cone spectral sensitivities (or LMS fundamentals) for each observer as described above. More details can be found in our previous papers, but briefly each of seven parameters was varied to find the combination that best accounted for the matches, *i.e.*, produced the lowest mean squared errors in the LMS activations across all the SPDs. The mean best-fitting parameters are given in Table 1.

The improvements in the match predictions for the individually estimated cone spectral sensitivities can be seen in Figures 2 and 3, for 2° and 10° FOV, respectively.

The red dots in Figures 2 and 3 show the white matches in MacLeod-Boynton chromaticity coordinates for the various triplets predicted from the CIEPO06 2° and 10° standard observers. Clearly, there is a good deal of variability, which suggests sizeable individual differences between our observers and the mean CIEPO06 observers. Observer variability, calculated from repeated matches, is roughly constant with age, while the inter-observer variability is somewhat higher for the youngest and the older age groups.

We then used the fitted LMS CMFs to estimate the triplets in MacLeod-Boynton chromaticity coordinates that match the white standard, adjusted so that the reference for each individual coincides with that of the CIEPO06 standard observer.

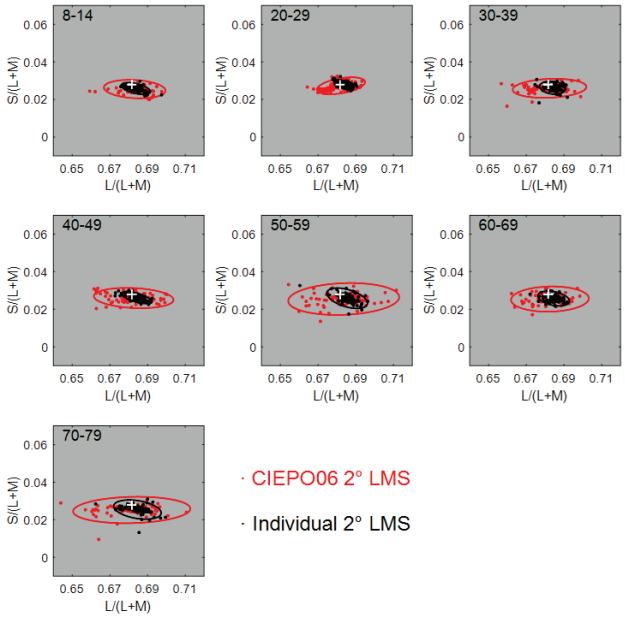

Figure 2. 2° color matches for different age groups plotted in MacLeod-Boynton chromaticity space. Each dot represents a single match for a single observer. Red dots were calculated using the CIEPO06 standard observer CMFs, while the black dots were calculated from the individually fitted CMFs. Ellipses denote 95% confidence limits. The white crosses indicate the reference white for the CIEPO06 standard observer.

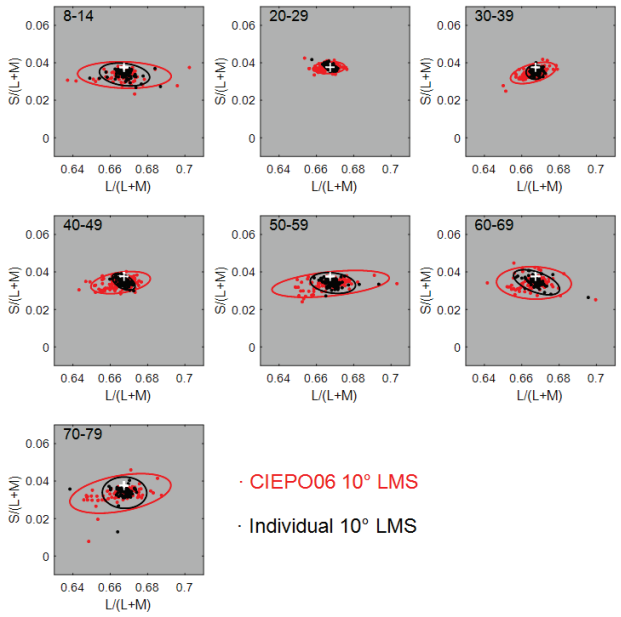

Figure 3. 10° color matches for different age groups plotted in MacLeod-Boynton chromaticity space. Details as Figure 2.

These are shown by the black dots and ellipses in Figures 2 and 3. The improvements in the match predictions can be seen by comparing these with the red dots and ellipses that were derived using the CIEPO06 standard observer. As can be seen, the results are impressive, and the scatter is much reduced. For the CIEPO06 standard 2° and 10° LMS, the averaged distance from each point to the mean in $\Delta l_{mb}s_{mb}$ are 5.55 and 5.40 x 10^{-3}, respectively. For the individual 2° and 10° LMS, the average distances from each point to the mean are 2.98 and 2.70 x 10^{-3}, respectively.

Additionally, 22 color deficient observers made color matches under the same methods as the color normal observers. We then fitted the same model to SPDs of their color matches and found that for 20 observers the model predicts shifts of the correct cone type for their diagnosis, with most (n=15) shifts in the range of 17-19 nm, consistent with other estimates of spectral shifts for anomalous trichromats (15) while 5 observers had slightly smaller shifts (10-16 nm), and the data from a further two observers produced fits were consistent with them having normal color vision.

4. Conclusions

In this paper, we review the results our earlier work (6-8). We estimated 122 normal and color vision deficient observer's photopigment, macular and lens optical densities and their L- and M-cone photopigment spectral shifts, and thus obtained their individual cone spectral sensitivities. The average individual differences across normal observers were found to differ slightly from the CIEPO06 standard or mean observer with +2.53 and -1.97 nm shifts of the M- and L-cone photopigments, respectively, and a 43-45% denser 2-deg macular pigment density, as well as slight differences in some cone optical densities. There was a gradual increase in lens density with age and unexpectedly a small increase in L-cone optical density, but other factors showed relatively little correlation with age. Older observers showed more inter-observer variability, but intra-observer variability was relatively fixed across the age span. Although increases in L- and M-cone optical densities with age have been reported (16), we find no evidence for an increase in M-cone optical density with age and in fact there is a non-significant negative trend in our fits (8). We suspect some of the small, unexpected changes in optical density, such as the increase in L-cone optical density with age, might be an artefact of the fitting procedure resulting from discrepancies in the shape of the lens template assumed in CIEPO06. Furthermore, in our previous study (7) we found that several parameters were strongly correlated in the fits, including lens density, L- and M-cone spectral shifts and L- and M-cone optical densities.

The parameter estimates we found suggest that for our population of observers, small adjustments to the CIEPO06 LMS (and thus their linear transform the CIE 2015 XYZ CMFs), particularly to the L- and M-cone peak sensitivities, and to the macular pigment density better predict their color matches. Further verification of our methodology and model will require measurements such as cone spectral sensitivities, color matches, and lens and macular densities preferably using monochromatic lights, as well as a molecular genetic analysis of the observer's photopigment genes, but these are beyond the scope of this study. Nevertheless, we have shown that the use of individual CMFs significantly reduces the matching errors predicted by standard CMFs. Such individualized specifications will be important for color critical applications, but we note that more appropriate metrics for quantifying color differences for individual observers are required.

The experimental method and model also allowed us to estimate color matching functions of anomalous trichromats. In the majority of cases, the predicted spectral shift of the anomalous cone was about 19 nm.

If we are to usefully relate these individual differences in cone spectral sensitivities to differences in color appearance, then models of color appearance that explicitly link color appearance to the L-, M- and S-cone spectral sensitivities will be required. Most current appearance models have been manipulated and adjusted to predict color differences using the flawed 1931 XYZ CMFs and are therefore inappropriate for LMS cone spectral sensitivities.

5. Impact of Your Research

Our research presents a powerful method of estimating and generating individual color matching functions for normal and color deficient human observers. Such functions can compensate for the known individual differences between observers and enable display devices and color reproduction to be individually optimized. Consequently, this work addresses the growing demands for personalized color accuracy and will help overcome the challenges of observer metamerism failures and so ensure that color reproduction remains consistent and accurate for individual observers across a wide range of environments.

6. Acknowledgements

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7. References

1. CIE. Fundamental chromaticity diagram with physiological axes – Part 1. Vienna: Central Bureau of the Commission Internationale de l' Éclairage; 2006.
2. Stockman A, Sharpe LT, Fach CC. The spectral sensitivity of the human short-wavelength cones. Vision Res. 1999;39(17):2901-27.
3. Stockman A, Sharpe LT. Spectral sensitivities of the middle- and long-wavelength sensitive cones derived from measurements in observers of known genotype. Vision Res. 2000;40(13):1711-37.
4. Stockman A, Rider AT. Formulae for generating standard and individual human cone spectral sensitivities. Color Research & Application. 2023;48(6):818-40.
5. Stockman A, Sharpe LT. Cone spectral sensitivities and color matching. In: Gegenfurtner K, Sharpe LT, editors. Color vision: From Genes to Perception. Cambridge: Cambridge University Press; 1999. p. 53-87.
6. 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 Research & Application. 2024;2024:417-534.
7. Shi K, Luo MR, Rider AT, Song S, Huang T, Stockman A. Individual differences in color matches and cone spectral sensitivities in 51 young adults. Opt Express. 2024;32(13):23597-616.
8. Shi K, Luo MR, Rider AT, Siyuan S, Huang T, Stockman A. Individual color matches and cone spectral sensitivities in 100 observers of varying age. Opt Express. in press.
9. 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(8):12292-306.
10. Hu Y, Wei M, Luo MR. Observer metamerism to display white point using different primary sets. Opt Express. 2020;28(14):20305-23.
11. Huang M, Li Y, Wang Y, Li X, Wei M. Effect of primary peak wavelength on color matching and color matching function performance. Opt Express. 2021;29(24):40447-61.
12. Shi K, Luo MR. Factors affecting colour matching between displays. Opt Express. 2022;30(15):26841-55.
13. 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(4):5670-86.
14. Berns RS, Motta RJ, Gorzynski ME. CRT colorimetry. part I: Theory and practice. Color Research & Application. 1993;18(5):299-314.
15. DeMarco P, Pokorny J, Smith VC. Full spectrum cone sensitivity functions for X-chromosome linked anomalous trichromats. J Opt Soc Am A. 1992;9(9):1465-76.
16. Renner AB, Knau H, Neitz M, Neitz J, Werner JS. Photopigment optical density of the human foveola and a paradoxical senescent increase outside the fovea. Visual Neurosci. 2004;21(6):827-34.