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Predicting color matches from luminance matches

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Color vision and spectral sensitivity vary among individuals with normal color vision; thus, for many applications, it is important to measure and correct for an observer's sensitivity. Full correction would require measuring color and luminance matches and is rarely implemented. However, luminance matches (equiluminance settings) are routinely measured and simple to conduct. We modeled how well an observer's color matches could be approximated by measuring only luminance sensitivity, since both depend on a common set of factors. We show that lens and macular pigment density and L/M cone ratios alter equiluminance settings in different ways and can therefore be estimated from the settings. In turn, the density variations can account for a large proportion of the normal variation in color matching. Thus, luminance matches may provide a simple method to at least partially predict an observer's color matches without requiring more complex tasks or equipment.

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1. INTRODUCTION

Color vision varies widely across the normal population. These variations arise from many sources and affect many perceptual judgments about color, from the stimuli that match or appear metameric, to how the appearance of different spectra are described [1]. Accordingly, the "standard observer" is often a poor characterization of the sensitivity and performance of any individual observer, and there is often a need to empirically determine an individual's sensitivity. An example is the widespread practice of measuring and correcting for individual differences in an observer's luminance sensitivity [2].

Differences in spectral sensitivity are also important to account for in order to communicate color information across observers. Just as there is color profiling for devices—in order to ensure that the colors produced by one medium (e.g., a display) are reproduced by another (e.g., a printer)—for certain applications, it is valuable to ensure that the colors discriminable to one observer can be faithfully reproduced by the visual system of another observer. Thus, a color profile could similarly be incorporated into the color management system to account for the idiosyncratic sensitivity of each observer.

The need for human color profiling has increased with the recent introduction of high dynamic range and wide gamut lighting and displays, such as the newer generation of monitors, TVs, and projectors using LEDs, OLEDs, or lasers [3]. These systems rely on primaries with more narrowband spectra, which increase the gamut of possible colors and also increase the potential for differences in perception across observers [4,5]. Maintaining consistent experiences across observers thus would benefit from separate calibrations of the display for each observer [6]. However, practical and efficient techniques for performing this calibration remain lacking.

Full characterization of an observer's color vision would require deriving the individual's spectral sensitivity. This is usually estimated by measuring color-matching functions and luminance matches. Both are known to be affected by a number of physiological sources of variation, including the density of the lens and macular screening pigments as well as the spectral peaks and optical density of the cone photopigments [7–10]. Color matches alone are insufficient because they are unaffected by the relative sensitivity or ratio of the different cone classes (because the match depends on equating sensitivity within each independent cone class). As a result, color matches do not provide information about individual differences in cone ratios. Luminance settings under most conditions depend only on the summed activity of the L and M cones [11,12] (though under some conditions there can be weak contributions from S cones [13,14]). Thus, luminance settings are strongly affected by, and can provide information about, interobserver differences in the ratio of L to M cones [15] yet provide little information about S cone sensitivity.

Because the sources of variation affecting spectral sensitivity are limited in number [7,8], in theory a small number of measurements (e.g., color matches) could suffice to completely describe the individual's colorimetric properties [16,17]. This could be done wholly empirically, by measuring the matches that best characterize the observer values for the basic functions describing the inter-observer variability. For example, a small number of measurements can be used to specify the spectral sensitivities of individual cameras, since the sources of variation in the sensors are, again, small in number [18]. However, color matching can be time-consuming and a difficult task for observers and also requires specialized equipment. Thus, it may be a difficult test to apply in many settings.

An alternative approach would be to directly estimate the values of the physiological factors (e.g., the density of the lens or macular pigment) and then reconstruct the observer's spectral sensitivities from these estimates. A number of procedures have been developed for these assessments. For example, lens pigment density can be estimated by dark adapting observers and then comparing scotopic luminance settings to the sensitivity predicted by rhodopsin [19]. Macular pigment density can be estimated by comparing the luminance settings in the fovea and periphery [20–22]. Further, cone ratios (specifically, the relative number of long- and medium-wavelength [L and M] cones) can be estimated from psychophysical or ERG measurements of photopic luminance sensitivity [15,23]. Physiological factors affecting sensitivity can also be measured from color matching [7,17,24]. However, many of these procedures are, again, time-consuming and may require special hardware.

In this study, we modeled the potential to approximate an individual's spectral sensitivity from luminance matches alone using simple and established measures to characterize individual differences in luminance sensitivity. These have the advantage that they can be easily implemented and assessed on the types of displays that are actually being calibrated. An individual's luminosity function or "sensation luminance" [25] can be rapidly and reliably measured by a number of techniques, including heterochromatic flicker photometry [22] and minimum motion paradigms [26]. As noted, the variations in luminance are known to reflect variations in the densities of the prereceptoral screening pigments and the relative number of the L and M cones as well as other factors that might influence the L and M cone fundamentals. In turn, lens and macular pigment density are known to be two of the most important factors affecting spectral sensitivity and thus color matching [7,8]. We therefore asked whether luminance matches—of the type that are commonly measured for color displays—could recover estimates of lens and macular pigment density and how well this information alone could be used to approximate the observer's color matches.

We explored this question in two stages by modeling (rather than empirically measuring) individual differences in luminance and color-matching functions. In the first stage, we show that lens pigment density, macular pigment density, and cone ratios lead to distinct changes in equiluminance settings and thus that estimates of these physiological factors can be derived from the individual's luminance settings. In the second stage, we evaluate how well incorporating these estimates can predict variation in the color matches of color-normal observers simulated to encompass the typical range of full variation in spectral sensitivity. These analyses suggest that luminance matches alone could provide a good first approximation of color matches and thus that a significant proportion of observer variation in spectral sensitivity could be corrected using a task that is efficient and easy to administer on many color displays.

2. METHODS AND RESULTS

A. Recovering Sources of Sensitivity Variation from Luminance Settings

Luminance sensitivity is typically measured by varying the relative intensity of a spectral stimulus until its luminance is equated for a fixed reference stimulus. Often the stimuli are the RGB primaries of the display. In flicker photometry, the matches are made by rapidly alternating the two lights so that the color alternation is not visible and the stimulus only appears to flicker in brightness [11,27]. The luminance match occurs when the flicker is minimized. In minimum motion, luminance efficiency is instead measured by varying the relative intensities of the two colors composing a counterphasing grating and then pairing this in spatiotemporal quadrature phase with a counterphasing achromatic grating. The gratings appear to drift in different directions depending on which color has a higher luminance; thus, the match occurs when the motion is nulled [26]. An important feature of such tasks is that the resulting luminance settings are linear and, therefore, all lie within an "equiluminant plane" in tristimulus space [2]. This has the advantage that the relative settings for only three noncolinear points are required to specify the plane and predict the settings that would occur for any other pair of chromaticities. For example, measuring how the red and green primaries of a display must be adjusted to match a fixed level of the blue primary is sufficient to fully define the plane.

In this study, we asked how well these measurements can in turn be used to estimate the color characteristics of the observer. This depends on whether different physiological factors tilt the plane in similar or different ways. To assess this, we focused on the three principal sources of variation in luminance sensitivity, which, again, are L/M cone ratio, lens pigment density, and macular pigment density. For these, we adopted a standard observer based on the following parameters. The lens absorption was taken from the transmittance function for a 32-year-old observer with a mean density of 1.6 at 400 nm [28]. For macular pigment, we used the spectral transmission [29] with a mean peak density of 0.495 at 460 nm. Finally, for the cone spectral sensitivities, we used the Smith and Pokorny fundamentals [30], which are normalized in relative sensitivity consistent with an L/M cone ratio of 1.6. We chose these fundamentals because they have been widely used for color research as the basis for a common chromaticity diagram [31], though more precise estimates of the cone sensitivities are available and are supplanting these as a standard [32]. The specific pattern of changes would depend on the specific choice of spectra. However, the implications of the present analyses do not depend on this choice, as our aim is to show in principle how, for any assumed set of spectral sensitivities, the physiological variations can be estimated from luminance settings and applied to color matches.

We first explored how luminance matches between different sets of primaries would be biased by variations in these

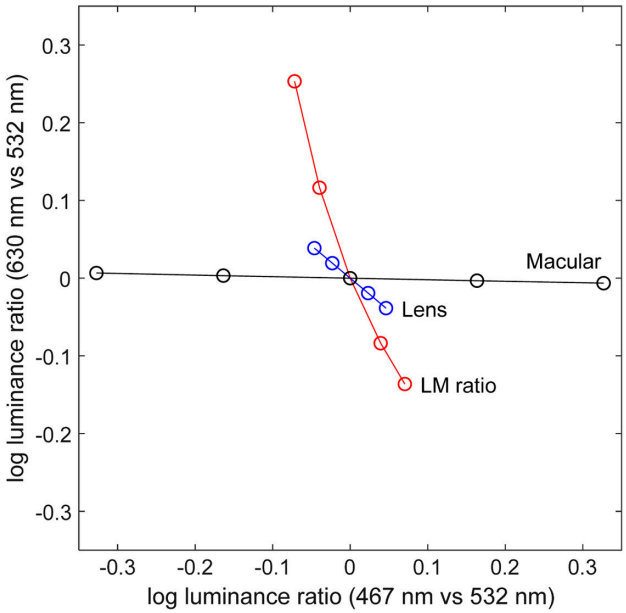

Fig. 1. Biases in luminance matches, relative to a standard observer, produced by variations in spectral sensitivity. Primaries are spectra peaking at 467, 532, or 630 nm (sd = 5 nm). Variations corresponded to ±2 standard deviations in the lens (sd = 18.7%) or macular (sd = 36.5%) pigment density, or to ±4-fold change in L to M cone ratio.

factors. The primaries were Gaussian spectra with different peak wavelengths and variable bandwidths. Figure 1 shows an example of three narrowband primaries approaching the rec. 2020 standard for wide gamut displays [3], with the red and blue primaries each matched to the green primary (rec. 2020 corresponds to the display characteristics recommended by the International Telecommunication Union for wide color gamut, standard dynamic range, and ultrahigh-definition television). The intensities were first adjusted to equate the luminances for the standard observer, so that any changes were relative to the settings for the standard observer. The figure shows the changes in the luminances required for each primary, as each of the physiological factors is varied over a range of values. Specifically, the curves illustrate the log change in matching luminance, as lens pigment density, macular pigment density, or L/M cone ratio is varied relative to the standard observer (for which the matches would be at zero). It is evident from this figure that the three factors tilt the equiluminant plane in distinct ways. For example, macular pigment variations only affect the blue versus green settings, L/M ratios predominantly affect the red versus green settings, and lens pigment density affects both. These differences suggest that the values for these factors can, in principle, be estimated from the tilt measured for the individual.

Since there are three factors, this estimation requires solving three equations representing how each factor would affect the matches between three independent pairs of primaries. Note that these primaries do not have to be the ones for which the matches are actually measured. As noted above, the linearity of luminance settings allows one to calculate the matches that would occur for any arbitrary set of primaries once the plane is specified.

The equation we used converts from a log change in one of the factors to a log change in the primary luminances and has the general form

$$\begin{pmatrix} \Delta_{P1} \\ \Delta_{P2} \\ \Delta_{P3} \end{pmatrix} = \begin{pmatrix} w_{L1} & w_{M1} & w_{R1} \\ w_{L2} & w_{M2} & w_{R2} \\ w_{L3} & w_{M3} & w_{R3} \end{pmatrix} \begin{pmatrix} \Delta L \\ \Delta M \\ \Delta R \end{pmatrix} \quad (1)$$

or

$$e = Wo, \quad (2)$$

where e represents the log change in the luminance ratio of the three primary pairs, and o represents the log change in the observer factors of lens pigment density (L), macular pigment density (M), and cone ratios (R).

The weights matrix W gives the relative change in luminance due to a given change in one of the factors and must be calculated for each set of primaries. For lens and macular pigment, the weights were designed to convert between a log change in density for the two primaries and the log change in luminance sensitivity, again relative to a standard observer. The log change was used because this leads to a linear relationship between the density change and the luminance change. As in the example above, the primaries were chosen to have Gaussian spectra with variable peak and bandwidth. The weights for the first pair were given by

$$w_{L1} = \log(\Delta P_{1a} \,/\, \Delta P_{1b}) \,/\, D_{\max}, \quad (3)$$

where P_{1a} and P_{1b} are the two primary spectra for pair 1, and ΔP_{1a} and ΔP_{1b} are the relative changes in the intensity of each primary due to filtering by the lens for the standard observer. The weights were normalized by the peak lens density ($D_{\max}$), which, as noted above, was taken as 1.6 at 400 nm for the standard observer. The same functions were used for the macular pigment weights, substituting the macular pigment transmittance and assuming a peak macular density of 0.495 at 460 nm (for a foveal target).

The effect of the cone ratios on the relative luminance settings depends on the relative L/M excitation for the two primaries:

$$\Delta R = \log(n), \quad (4)$$

$$w_{R1} = \log[(n * L_a * P_a + M_a * P_a) \,/\, (n * L_b * P_b + M_b * P_b)], \quad (5)$$

where L_a, L_b, and M_a, M_b are the cone responses to primaries a and b in pair 1, and n is the scaling of the L versus M cones relative to the standard observer ($n = 1$).

However, in this case, the luminance ratios vary nonlinearly with cone ratios (Fig. 1). Consequently, the conversion equation we illustrate is only approximately correct for this factor. However, the deviations are not pronounced over moderate changes in the cone ratios (e.g., the ±4 fold range illustrated in Fig. 1, which captures the range of variation in most but not all color-normal observers [33]) and could be corrected in practice by applying an additional transform.

Again, the resulting equation predicts the luminance matches an observer would make based on his or her physiological profile. The values for the three factors therefore can be estimated in

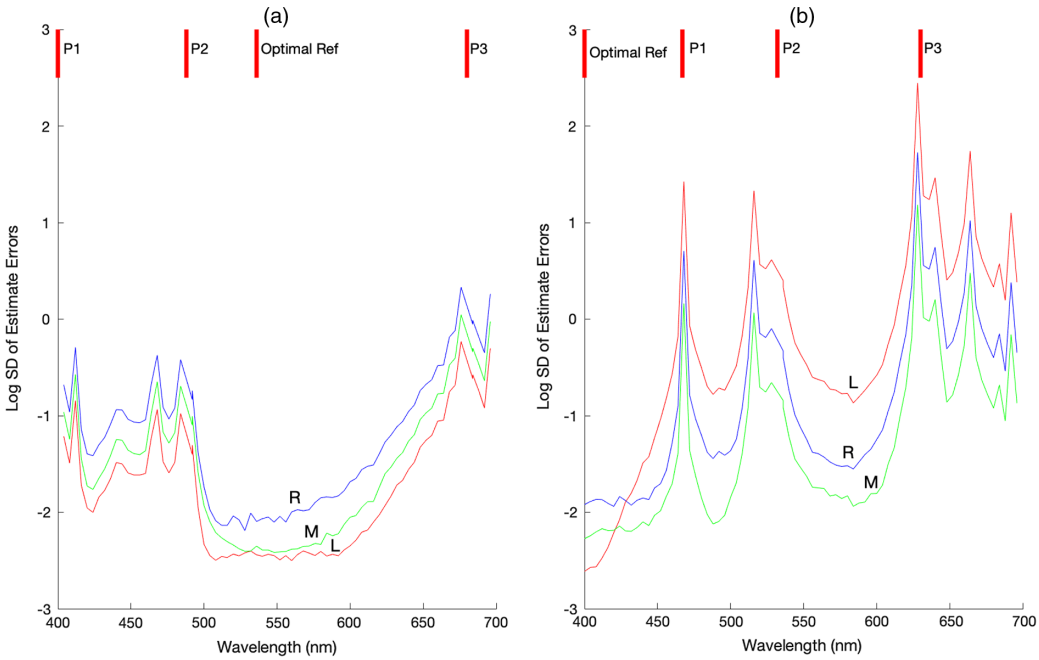

Fig. 2. Errors in the estimates of the lens and macular pigment density and L/M ratio introduced by errors in the luminance matches (simulated by adding Gaussian noise to the correct matches). Each plot shows the log standard deviation in the errors for estimating the lens (red line, L), macular (green line, M), and L/M (blue line, R) factors for a fixed set of primaries and a variable reference wavelength. The primary wavelengths and reference wavelength resulting in the smallest errors are indicated by the bars. (a) Primary wavelengths optimized for the lowest error. (b) The rec. 2020 primaries.

principle by measuring the observer's luminance matches and then inverting the equation

$$o = W^{-1}e. \tag{6}$$

The estimates for these factors could be corrupted in a number of ways. For example, they depend on assumptions about the physiological spectra and calibration of the display [34]. They are also obviously affected by the precision of the luminance measurements because an error in the matches would generate an error in the estimated profile for the observer. To explore the impact of such errors, we simulated the effects of adding Gaussian noise to the luminance matches such that the standard deviation of the noise was 1% of the primary luminance. We then calculated the error in the estimates of the physiological factors. Figure 2 shows an example of these simulations for a fixed set of three primaries as a function of the peak wavelength of the matched reference stimulus. In the first case, the peak wavelengths of the primaries were varied in a separate analysis to minimize the error; in the second case, they were fixed at the 467, 532, and 620 nm primaries of the rec. 2020 approximation. Errors are larger for the latter set. However, for both, the errors are generally small when the reference has a peak wavelength far removed from the primary peaks, while increasing in the neighborhood of the primaries.

A second general source of error is that we are only modeling some of the sources of variation in the observer's spectral sensitivity. The L and M cone sensitivities can also vary in their peaks (e.g., because of polymorphisms in the genes encoding the photopigments [35]) and in their bandwidths (e.g., because of variations in the optical density of the photopigments [36]). These variations could also have an impact on the luminance settings and contaminate the estimates of the preretinal screening or cone ratios (e.g., [37]). We evaluated this from Monte Carlo simulations of 1000 observers defined by random variations in the lens and macular density as well as the L and M spectral peaks and optical density. The standard deviations of these variations were taken from the values synthesized from a number of studies by [8] and were the same as for the color-matching functions described below. As noted, estimates of the L/M cone ratio can also be corrupted by variation in the cone sensitivities [37]. However, we did not model these errors because, unlike the lens and macular pigment variations, knowledge of the cone ratios is irrelevant for predicting the color matches (and unnecessary for the empirical specification of luminance sensitivity). The primaries again corresponded to the rec. 2020 approximation, and the reference wavelength again was varied. Luminance settings were calculated for the observers, and the inverse equation then applied assuming these settings reflected only the lens and macular pigment. Figure 3 shows the resulting errors (plotted as the log of the standard deviation of the percentage error across observers). In this case, the errors in the estimates are large for many wavelength pairs and are larger for the estimated density of the lens pigment than for the macular pigment. However, for some reference and primary combinations they approach just a few percent of the nominal estimates, suggesting that some comparisons can yield accurate information about the factors.

B. Predicting Color-Matching Functions from the Observer Profile

The preceding analyses asked how well one could estimate an observer's inert screening pigment densities from measurements

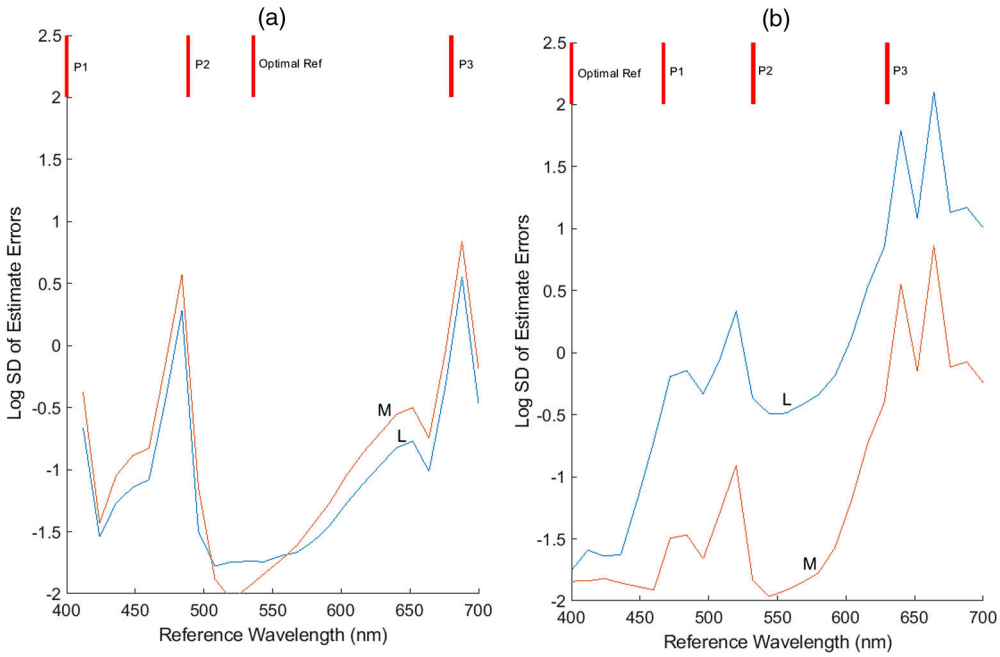

Fig. 3. Simulations of the errors in the estimated lens and macular pigment density resulting from unknown variations in the λ_{max} and optical density of the cone pigments. The standard deviation of the errors in predicted density of the lens (blue line, L) or macular (red line, M) pigment are plotted as a function of wavelength, again, for (a) primary wavelengths optimized for the lowest error and (b) the rec. 2020 primaries.

that are routinely used to characterize luminance efficiency. Here, we ask how well these measurements could predict the observer's color-matching functions. Again, this prediction must be only approximately correct because a number of additional factors affect spectral sensitivity and thus color matching. The question is whether there are meaningful improvements in the predictions beyond the standard observer. As also noted previously, color matches are unaffected by cone ratios; thus, the estimates that could be derived for the L/M ratio from luminance matches are not relevant to the present color-matching task.

To assess this, we again used Monte Carlo simulations to construct observers with varying spectral sensitivities defined by random variations in the factors known to affect color matching. The standard deviations for each normally distributed variation were taken from [8]. The factors included (1) lens pigment density (sd = 18.7% or 0.3 at 400 nm); (2) macular pigment density (sd = 36.5% or at 460 nm); (3) independent variation in the spectral peak λ_{max} for each cone (sd = 2.0, 1.5, or 1.3 nm for L, M, or S cones, respectively); and (4) independent variation in the optical density of the cone pigments (sd = .09 for L and M, and .074 for S). Each simulated observer was constructed by (1) removing the assumed lens and macular filtering from the Smith and Pokorny fundamentals; (2) shifting the spectrum along the wavenumber axis to the chosen λ_{max}; (3) adjusting the optical density independently for each cone assuming an initial density of 0.35; and finally (4) screening by the random values for the lens and pigment density. Equations for each of these steps can be found in [7].

Color matches were calculated for primaries and test spectra that were again defined by Gaussian spectra with varying peaks and bandwidths. The matches are given by the following standard equation:

$$\begin{pmatrix} L_t \\ M_t \\ S_t \end{pmatrix} = \begin{pmatrix} w_{L1} & w_{L2} & w_{L3} \\ w_{M1} & w_{M2} & w_{M3} \\ w_{S1} & w_{S2} & w_{S3} \end{pmatrix} \begin{pmatrix} P_1 \\ P_2 \\ P_3 \end{pmatrix}, \tag{7}$$

or

$$c = Wp, \tag{8}$$

where c gives the cone responses to the test stimulus, p gives the radiances of the primaries, and W gives the responses of each cone to a unit level of each primary. As in the preceding case, the matches are determined by calculating the response of each cone to the test stimulus and then inverting the equation to solve for the primaries:

$$p = W^{-1}c. \tag{9}$$

Figure 4 illustrates an example of the calculations for a single observer chosen to differ from the standard observer by 1 standard deviation along each of the modeled factors. Panel a compares the cone spectra for the individual and the standard observer. Panel b shows the color matches based on primaries again at 467, 532, and 630 nm ($s\,d = 5$ nm) for 24 test spectra ranging from 400 to 700 nm in 12 nm steps. The three curves in this plot shows three conditions: (1) the standard observer; (2) the individual modeled by all factors; and (3) the individual modeled only by lens and macular pigment. Comparisons of 1 versus 2 show the errors in applying no individual correction, 1 versus 3 shows the improvements by correcting only for the prereceptoral screening, while 2 versus 3 shows the residual errors without the full correction. To visualize these errors, panel

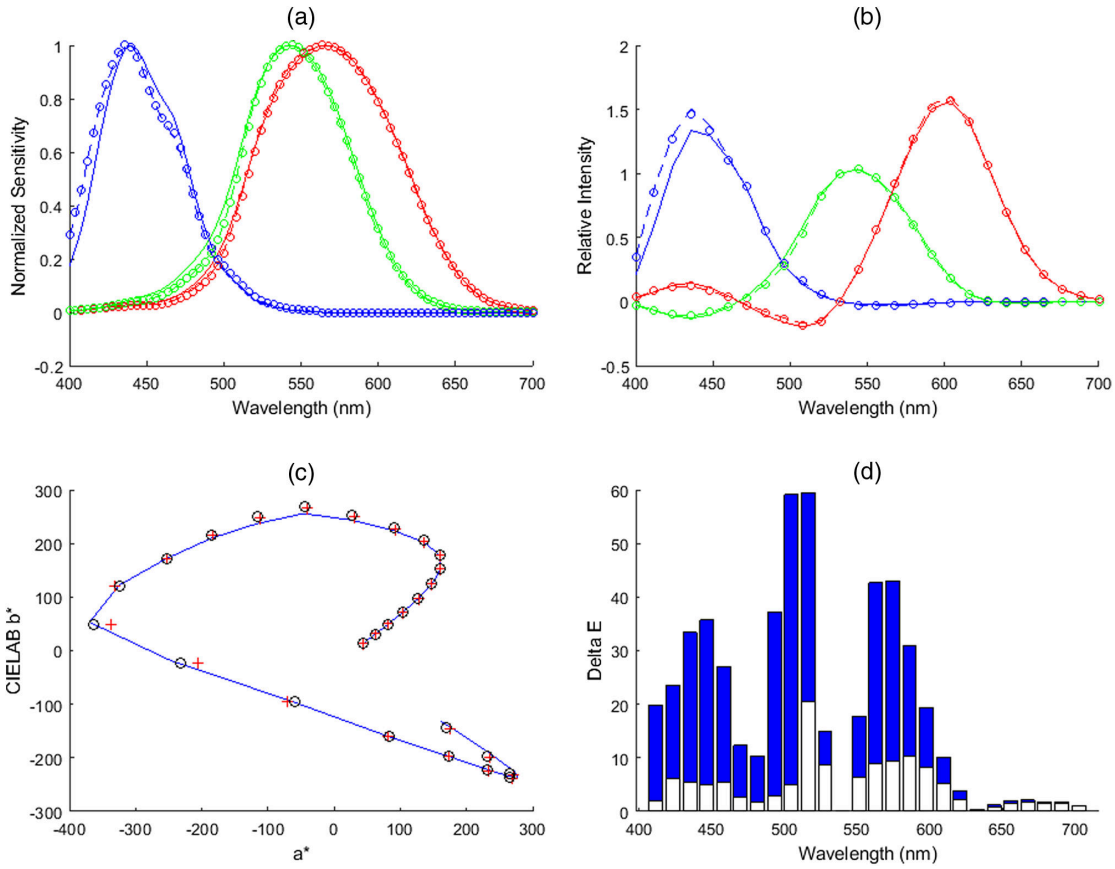

Fig. 4. Example of color matches predicted from the luminance matches for a single observer differing from the standard observer by 1 sd in all factors. Shown are (a) spectral sensitivity and (b) color-matching functions of the actual individual (dashed line), the individual approximated only from the lens and macular pigment density (open circles), and the standard observer (solid line). (c) Coordinates of the matches in the CIELAB color space, for the full observer (red plus signs), lens and macular only (open circles), and standard observer (solid line). (d) Absolute errors (delta E) in the predicted matches between the actual versus standard observer (blue) or the actual versus lens and macular approximation (white).

c of Fig. 4 plots the coordinates of the matches within the $a*b*$ plane of the CIELAB uniform color space, while panel *d* plots the difference between the settings in terms of ΔE (a measure of the perceptual magnitude of a color difference), based on the Euclidean difference in the coordinates (across all three dimensions of CIELAB) for the standard observer versus either version of the modeled observer. These plots reiterate the large and visible ($\sim \Delta E > 1$) differences in color matches that result from normal variations in spectral sensitivity and also show that knowing only the lens and macular pigment density of the individual allows good approximation of their matches. In particular, across the set of test stimuli, the error in the predicted matches is reduced to roughly 24% or one-fourth of the error from assuming the standard observer, as indicated by the relative heights of the white and blue bars in Fig. 4(d). In other words, in this specific case, 76% of the difference between the individual and standard observer is due to the difference in lens and macular pigment density.

To more generally evaluate these trends, we repeated the matches for 1,000 simulated observers varying in each of the factors as described above. The matches were evaluated for the same primaries as for the single observer illustrated in Fig. 4 as well as for a second set with the same peak wavelength but wider bandwidth (sd = 10 nm). Figure 5 shows the mean errors in the predicted matches, again, with or without applying the correction for lens and macular density. The correction reduced the average errors to 28% or 23% of the uncorrected errors for the narrower and broader primaries, respectively, with a residual average error of 11.1 or 13.0 ΔE units (compared with a mean of 39.4 or 56.5 for the uncorrected matches).

In the final example, we compared the matches predicted for more desaturated, broadband spectra, again matched by the narrowband (sd = 5 nm) or broadband (sd = 10 nm) primaries. The test spectra in this case were taken from the reflectance spectra of the MacBeth Color Checker [38] under equal energy illumination. Matches to these were, again, calculated for a sample of 1,000 randomly varying observers. The histograms in Fig. 6 show the average errors in the matches predicted for the 24 samples. In this case, the mean error is 13.9 (narrow primaries) or 12.0 (broad) ΔE but is reduced to 5.3 (38%) or 4.8 (40%), respectively, by including the lens and macular pigment estimates. Thus, again the estimates of the lens and macular pigment variations alone account for about 60% of the variation in the matches.

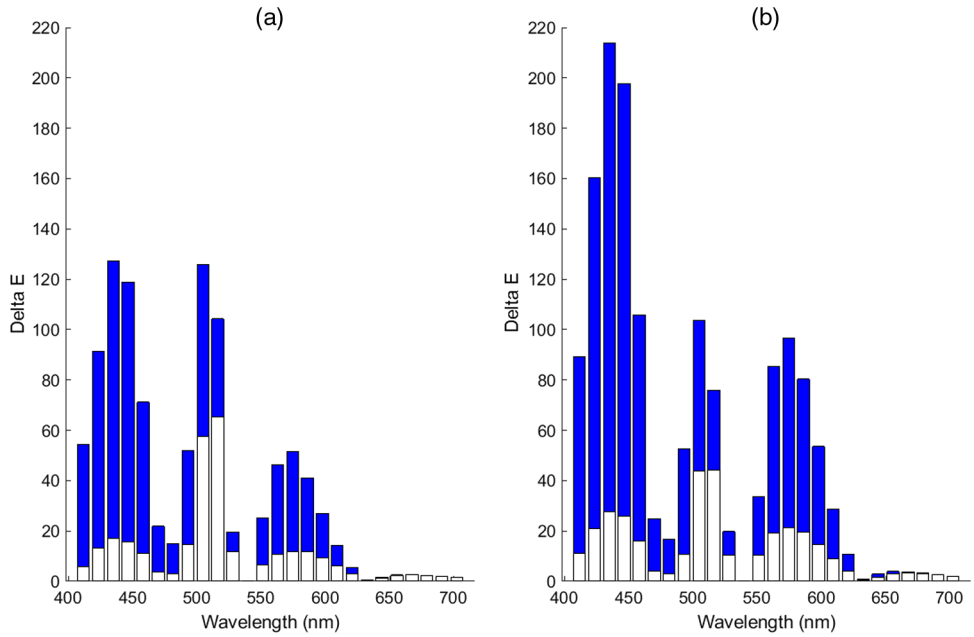

Fig. 5. Average estimated errors (delta E) in the color matches for different reference wavelengths predicted for a random sample of observers based on either the standard observer (blue) or from the lens and macular estimates (white). The two panels show the errors for the rec. 2020 primaries with narrow (5 nm; panel a) or broader (10 nm; panel b) bandwidths.

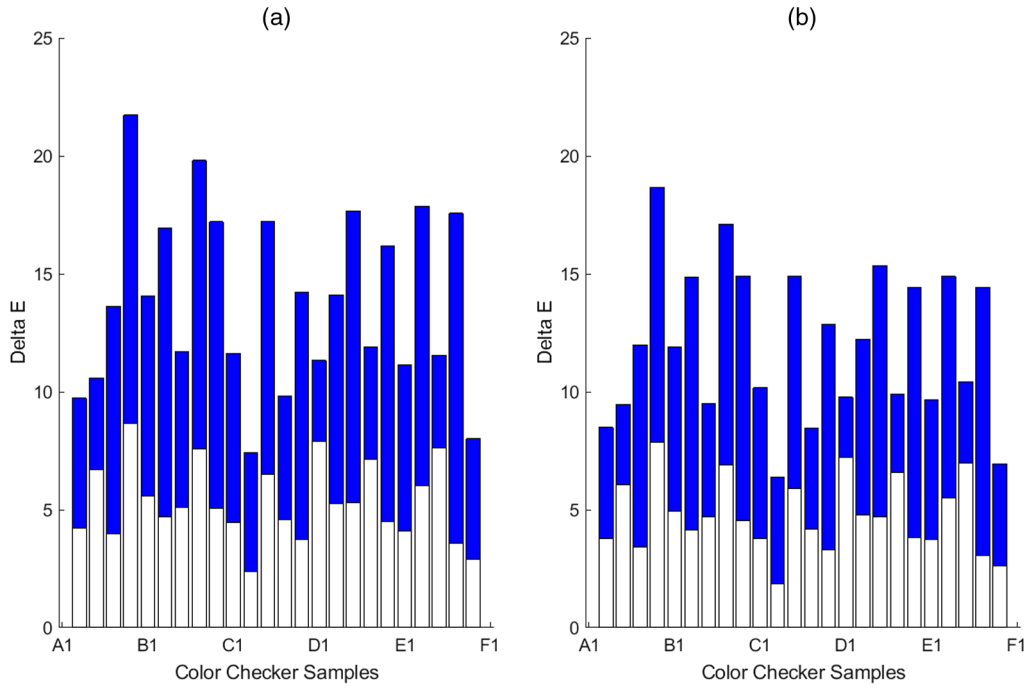

Fig. 6. Average estimated errors (delta E) in the color matches to the spectra of the MacBeth Color Checker predicted for a random sample of observers based on either the standard observer (blue) or from the lens and macular estimates (white). The two panels show the errors for the rec. 2020 primaries with narrow (5 nm; panel a) or broader (10 nm; panel b) bandwidths.

3. DISCUSSION

To summarize, normal variations in the spectral sensitivities of the cones are well recognized and well understood but are often ignored in many color applications and even in many scientific investigations of color vision. Recent work has emphasized the importance of incorporating individual differences into the design of color metrics [8]; further, these differences may become more important to evaluate and account for with the advances in color technology afforded by modern wide-gamut devices. However, there are currently few standardized methods for evaluating and incorporating these differences.

In this study, we considered a case where empirical measurements of spectral sensitivity are frequently conducted in order to assess and correct for the luminance sensitivity of the observer. Measurements of luminance sensitivity have a long history but were brought to the fore by the plethora of studies attempting to isolate "pure color" sensations and their potential neural substrate in order to understand the capacities and functions of different visual subsystems (specifically, silencing the magnocellular pathway to isolate the parvocellular and koniocellular pathways of pre-cortical color coding) (e.g., [2,27,39]). Regardless of whether they achieved this goal, the explosion of studies using equiluminant patterns led to highly developed and well-established and documented procedures for measuring the luminance sensitivity of the individual. These procedures are easy to implement on many displays and involve measurements that are simple, intuitive, and quick for naïve observers. They can also be highly precise because they tap signals for which the visual system is highly sensitive. They, therefore, potentially provide an efficient strategy for approximately calibrating monitors for the spectral sensitivities of users.

Our analyses suggest that the information that can be extracted from luminance matches about the density of an observer's screening pigments can go a long way in predicting the color matches an observer will make. This is to be expected because variations in prereceptoral screening are known to be a major source of variation in normal trichromatic color vision [7–9]. Moreover, the same settings provide information beyond color matching about the L/M cone ratios and thus luminance sensitivity. As such, they are a requisite of a complete specification of the observer. While they may be necessary, our work shows that, for some applications requiring only an approximate correction, they may also be sufficient, rendering separate procedures such as color matching unnecessary. Clearly, the adequacy of this correction will depend on the task and the precision of the measurements. However, our approach offers a potentially valuable compromise for color profiling that corrects for much of the errors introduced by not calibrating for the observer, using standard procedures that are efficient and easily implemented on many of the relevant media. Specifically, we have shown that standard luminance sensitivity estimates, without additional hardware or measurements, could already in principle correct for most of the individual differences in normal spectral sensitivities and color-matching functions. Moreover, while the present algorithm was developed as a proof of concept, it could be elaborated in a number of ways or combined with other techniques (e.g., limited color matches) to increase precision of the calibration.

It is possible that this approach could also have applications for other problems in color science. For example, many studies have assessed the properties of color coding by designing their experiments and stimuli in terms of the "cardinal directions" of color space [40]. These correspond to differences in the L and M cone signals at constant luminance (LvsM) or differences in S versus the L and M signals at constant luminance (SvsLM), and are important because they are thought to reflect the two dimensions along which chromatic information is represented in the retina and lateral geniculate [41]. Physiologically defined color spaces or diagrams based on these axes are popular for isolating these axes and more generally for specifying stimuli and interpreting results directly in terms of the cone excitations or cardinal mechanisms [31,42]. However, while most studies empirically determine constant luminance within the space for individual observers, it is rare for studies to attempt to similarly calibrate the observer for the chromatic directions that isolate their LvsM and SvsLM axes. This may be because, while methods for these calibrations have been developed [12,43,44], they can be more difficult to implement and remain to be fleshed out. However, because the cardinal axes reflect combinations of the cone signals, they are affected by the same peripheral factors that have an impact on the sensitivities of the cones, including variations in the density of the lens and macular pigments. As such, the luminance corrections that are normally measured for the observer could imply corrections that should be applied to the cardinal axes, which again might significantly improve their specifications without the need for a separate measurement.

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REFERENCES

1. K. J. Emery and M. A. Webster, "Individual differences and their implications for color perception," Curr. Opin. Behav. Sci. **30**, 28–33 (2019).
2. P. Lennie, J. Pokorny, and V. C. Smith, "Luminance," J. Opt. Soc. Am. A **10**, 1283–1293 (1993).
3. H. J. Kim, M. H. Shin, J. Y. Lee, J. H. Kim, and Y. J. Kim, "Realization of 95% of the Rec. 2020 color gamut in a highly efficient LCD using a patterned quantum dot film," Opt. Express **25**, 10724–10734 (2017).
4. R. L. Alfvin and M. D. Fairchild, "Observer variability in metameric color matches using color reproduction media," Color Res. Appl. **22**, 174–188 (1997).
5. B. Bodner, N. Robinson, R. Atkins, and S. Daly, "Correcting metameric failure of wide color gamut displays," SID Symp. Dig. Tech. Pap., **49**, pp. 1040–1043 (2018).
6. E. Walowit, "Determination of individual-observer color matching functions for use in color management systems," Electron. Imaging **2019**, 96 (2019).
7. M. A. Webster and D. I. MacLeod, "Factors underlying individual differences in the color matches of normal observers," J. Opt. Soc. Am. A **5**, 1722–1735 (1988).
8. Y. Asano, M. D. Fairchild, and L. Blonde, "Individual colorimetric observer model," PLoS ONE **11**, e0145671 (2016).
9. V. C. Smith and J. Pokorny, "Chromatic-discrimination axes, CRT phosphor spectra, and individual variation in color vision," J. Opt. Soc. Am. A **12**, 27–35 (1995).
10. Y. Asano, M. D. Fairchild, L. Blondé, and P. Morvan, "Color matching experiment for highlighting interobserver variability," Color Res. Appl. **41**, 530–539 (2016).
11. A. Eisner and D. I. MacLeod, "Blue-sensitive cones do not contribute to luminance," J. Opt. Soc. Am. **70**, 121–123 (1980).
12. B. W. Tansley and R. M. Boynton, "A line, not a space, represents visual distinctness of borders formed by different colors," Science **191**, 954–957 (1976).
13. A. Stockman, D. I. MacLeod, and D. D. DePriest, "The temporal properties of the human short-wave photoreceptors and their associated pathways," Vision Res. **31**, 189–208 (1991).
14. J. Lee and C. F. Stromeyer, 3rd, "Contribution of human short-wave cones to luminance and motion detection," J. Physiol. **413**, 563–593 (1989).
15. H. Hofer, J. Carroll, J. Neitz, M. Neitz, and D. R. Williams, "Organization of the human trichromatic cone mosaic," J. Neurosci. **25**, 9669–9679 (2005).
16. A. Sarkar and L. Blondé, "Colourimetric observer categories and their applications in colour and vision sciences," in *CIE Centenary Conference* (2013).

17. Y. Asano, M. D. Fairchild, L. Blondé, and P. Morvan, "Multiple color matches to estimate human color vision sensitivities," in *International Conference on Image and Signal Processing* (Springer, 2014), pp. 18–25.
18. E. Walowit, H. Buhr, and D. Wüller, "Multidimensional estimation of spectral sensitivities," in *Society for Imaging Science and Technology—25th Color and Image Conference Final Program and Proceedings* (2017), pp. 1–6.
19. D. V. Norren and J. J. Vos, "Spectral transmission of the human ocular media," Vision Res. **14**, 1237–1244 (1974).
20. B. R. Wooten, B. R. Hammond, Jr., R. I. Land, and D. M. Snodderly, "A practical method for measuring macular pigment optical density," Invest. Ophthalmol. Visual Sci. **40**, 2481–2489 (1999).
21. L. T. Sharpe, A. Stockman, H. Knau, and H. Jagle, "Macular pigment densities derived from central and peripheral spectral sensitivity differences," Vision Res. **38**, 3233–3239 (1998).
22. R. A. Bone and J. T. Landrum, "Heterochromatic flicker photometry," Arch. Biochem. Biophys. **430**, 137–142 (2004).
23. D. H. Brainard, J. B. Calderone, A. K. Nugent, and G. H. Jacobs, "Flicker ERG responses to stimuli parametrically modulated in color space," Invest. Ophthalmol. Visual Sci. **40**, 2840–2847 (1999).
24. D. I. MacLeod and M. A. Webster, "Direct psychophysical estimates of the cone-pigment absorption spectra," J. Opt. Soc. Am. A **5**, 1736–1743 (1988).
25. P. K. Kaiser, "Sensation luminance: a new name to distinguish CIE luminance from luminance dependent on an individual's spectral sensitivity," Vision Res. **28**, 455–456 (1988).
26. P. Cavanagh, D. I. MacLeod, and S. M. Anstis, "Equiluminance: spatial and temporal factors and the contribution of blue-sensitive cones," J. Opt. Soc. Am. A **4**, 1428–1438 (1987).
27. B. B. Lee, P. R. Martin, and A. Valberg, "The physiological basis of heterochromatic flicker photometry demonstrated in the ganglion cells of the macaque retina," J. Physiol. **404**, 323–347 (1988).
28. J. Pokorny, V. C. Smith, and M. Lutze, "Aging of the human lens," Appl. Opt. **26**, 1437 (1987).
29. R. A. Bone and J. M. Sparrock, "Comparison of macular pigment densities in human eyes," Vision Res. **11**, 1057–1064 (1971).
30. V. C. Smith and J. Pokorny, "Spectral sensitivity of the foveal cone photopigments between 400 and 500 nm," Vision Res. **15**, 161–171 (1975).
31. D. I. MacLeod and R. M. Boynton, "Chromaticity diagram showing cone excitation by stimuli of equal luminance," J. Opt. Soc. Am. **69**, 1183–1186 (1979).
32. A. Stockman, "Cone fundamentals and CIE standards," Curr. Opin. Behav. Sci. **30**, 87–93 (2019).
33. J. Carroll, J. Neitz, and M. Neitz, "Estimates of L:M cone ratio from ERG flicker photometry and genetics," J. Vis. **2**(8):1, 531–542 (2002).
34. J. Golz and D. I. MacLeod, "Colorimetry for CRT displays," J. Opt. Soc. Am. A **20**, 769–781 (2003).
35. J. Winderickx, D. T. Lindsey, E. Sanocki, D. Y. Teller, A. G. Motulsky, and S. S. Deeb, "Polymorphism in red photopigment underlies variation in colour matching," Nature **356**, 431–433 (1992).
36. V. C. Smith and J. Pokorny, "Psychophysical estimates of optical density in human cones," Vis. Res. **13**, 1199–1202 (1973).
37. J. Carroll, C. McMahon, M. Neitz, and J. Neitz, "Flicker-photometric electroretinogram estimates of L:M cone photoreceptor ratio in men with photopigment spectra derived from genetics," J. Opt. Soc. Am. A **17**, 499–509 (2000).
38. C. S. McCamy, H. Marcus, and J. G. Davidson, "A color-rendition chart," J. App. Photog. Eng. **2**, 95–99 (1976).
39. M. Livingstone and D. Hubel, "Segregation of form, color, movement, and depth: anatomy, physiology, and perception," Science **240**, 740–749 (1988).
40. J. Krauskopf, D. R. Williams, and D. W. Heeley, "Cardinal directions of color space," Vision Res. **22**, 1123–1131 (1982).
41. B. B. Lee, "Color coding in the primate visual pathway: a historical view," J. Opt. Soc. Am. A **31**, A103–A112 (2014).
42. A. M. Derrington, J. Krauskopf, and P. Lennie, "Chromatic mechanisms in lateral geniculate nucleus of macaque," J. Physiol. **357**, 241–265 (1984).
43. H. E. Smithson, P. Sumner, and J. D. Mollon, "How to find a tritan line," in *Normal and Defective Colour Vision*, J. D. Mollon, J. Pokorny, and K. Knoblauch, eds. (Oxford University, 2003), pp. 279–287.
44. M. A. Webster, E. Miyahara, G. Malkoc, and V. E. Raker, "Variations in normal color vision. I. Cone-opponent axes," J. Opt. Soc. Am. A **17**, 1535–1544 (2000).