University of Nevada, Reno

Using equiluminance settings to determine the cardinal chromatic directions for individuals

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science

in Psychology

by

Alex J. Richardson

Dr. Michael A. Crognale/Thesis Advisor

December, 2022

THE GRADUATE SCHOOL

We recommend that the thesis
prepared under our supervision by

Alex Richardson

entitled

Using equiluminance settings to determine the cardinal chromatic directions for

individuals

be accepted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE

Michael A. Crognale, Ph.D.
Advisor

Michael A. Webster, Ph.D.
Committee Member

Jennifer L. Hoy, Ph.D.
Graduate School Representative

Markus Kemmelmeier, Ph.D., Dean
Graduate School

Dec, 2022

ABSTRACT

Color information is processed by the retina and lateral geniculate along principal dimensions known as the cardinal directions of color space. Individual differences impacting the direction of these cardinal axes exist within the normal population and are influenced by individual variation in lens density, macular pigment, photopigment opsins, photoreceptor optical density, and relative cone numbers. The same factors that influence color differences also impact luminance. We modeled and empirically tested how well tilts in the equiluminant plane are correlated with rotations in the cardinal axes. Our results show that – especially in the SvsLM axis – cardinal axis rotation can be partially predicted by luminance settings.

Table of Contents

Tables:

Table 1: Table 1 shows the single parameter correlations from Figures 1 and 3 (upper panels) as well as a multiple-correlations using both LvsM and SvsLM axis tilts simultaneously to predict the rotation of each of the hue axes (lower panels)

R^2 Model

	S tilt	LM tilt	S angle
LM tilt	0. 069		
S angle	0. 743	0. 007	
LM angle	0. 301	0. 6	0.2

R^2 Behavior

	S tilt	LM tilt	S angle
LM Tilt	0.008		
S angle	0.311	0.219	
LM angle	0.065	0.081	0.005

Multiple Correlation (Model)
Adjusted R^2 (combined LM and S tilt)

	S + LM tilt
S angle	0.764
LM angle	0.727

Multiple correlation (Behavior)
Adjusted R^2 (combined LM and S tilt)

|	S + LM tilt
S angle	0.427
LM angle	0.062

Table 2: Table 2 show the magnitude of the luminance tilts or chromatic rotations for each variable

| Individual Factor	SD				
	SD	S tilt	LM tilt	S rotation	LM rotation
Photopigment Optical Density	0.09	0.026	0.055	0.52	0.039
L-cone peak shift	2	0.029	0.34	0.3	0.26
Macular pigment	0.365	0.68	0.23	2.71	0.44
Lens density	0.187	0.26	0.32	0.95	0.33
LM ratios	0.3	0.35	1.96	0	1.04

Figures:

Figure 1. Behavioral (orange) and modeled (blue) data showing correlation between degree of chromatic rotation and tilt of the equiluminant plane
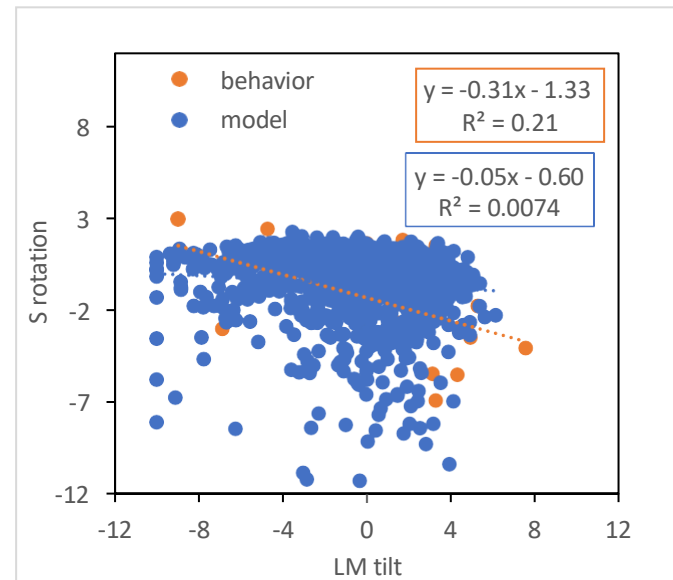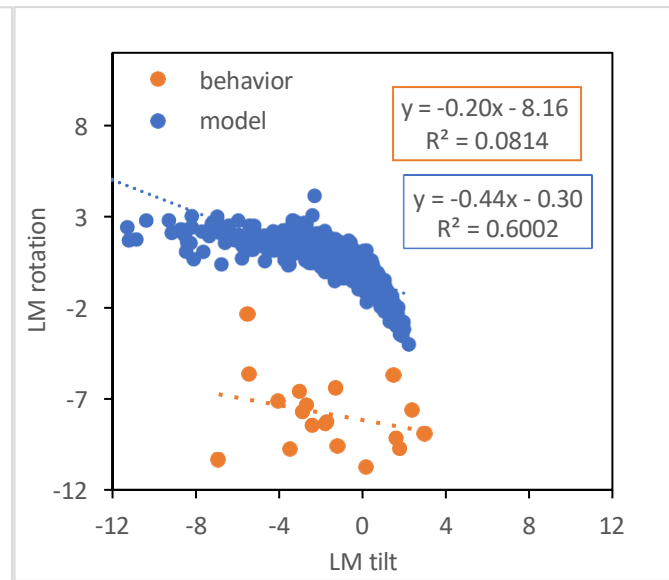
A.
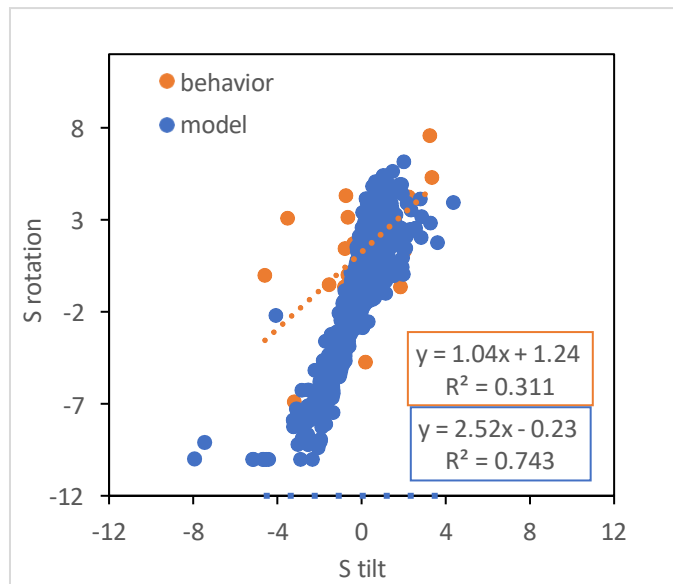
B.
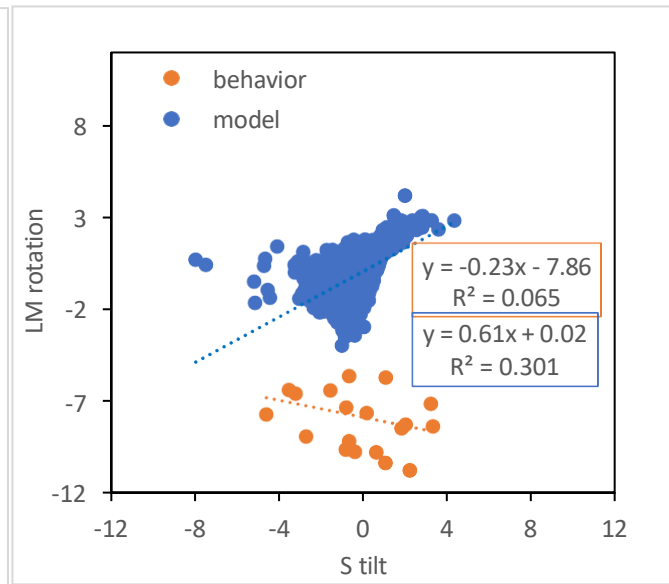
C.

D.

Figure 2: Figure 2 represents the correlations for tilt and rotation for each axis in the behavioral data – split between foveal and peripheral conditions.
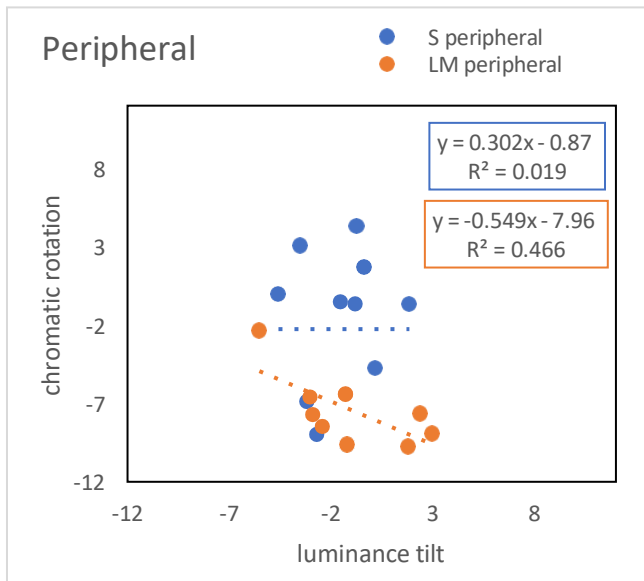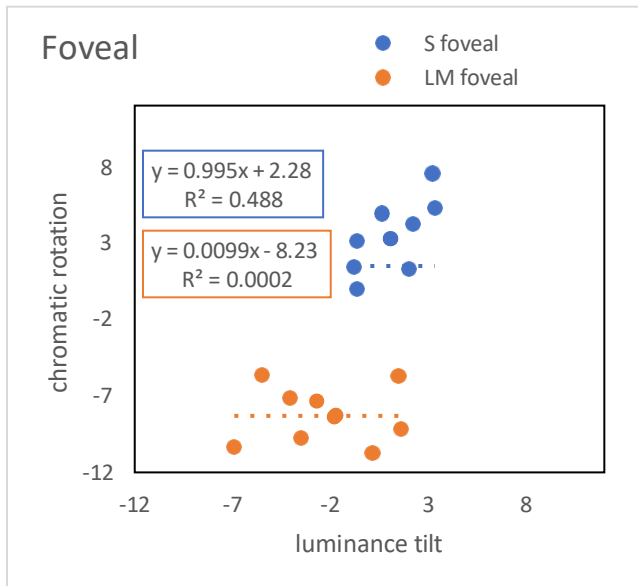
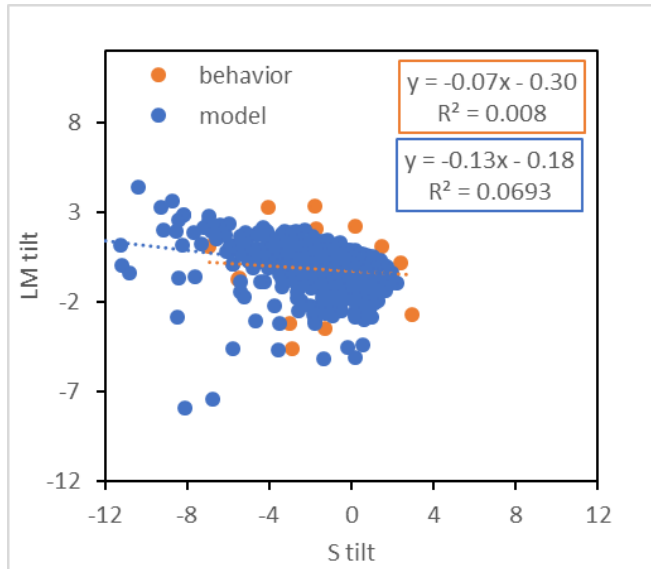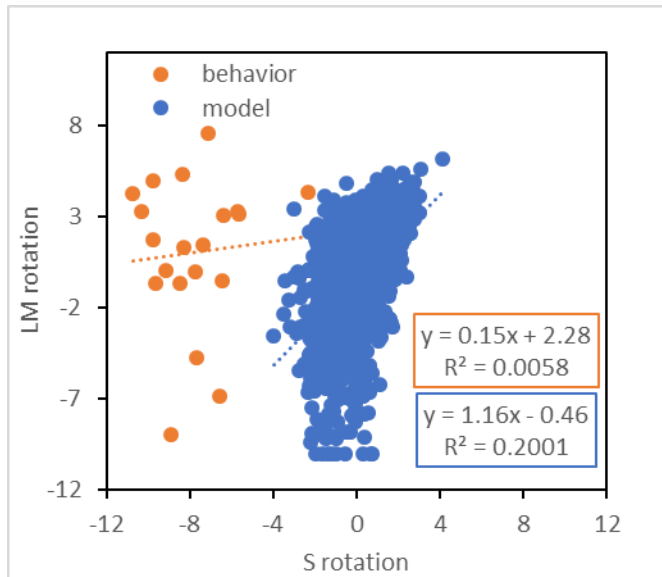Figure 3. Relationship between the tilts of the SvsLM and LvsM axes from the equiluminant

plane.

Fig 4. Relationship between the rotations of the SvsLM and LvsM axes within the equiluminant plane.

INTRODUCTION

In the retina and lateral geniculate nucleus (LGN), chromatic information is primarily encoded within mechanisms thought to represent two opponent dimensions of color [1]. These dimensions correspond to two physiologically distinct channels that difference the cone signals of the long-wavelength-sensitive (L) and medium-wavelength-sensitive (M) cones (LvsM) and difference the signals of the short-wavelength-sensitive (S) cones versus the L and M cones (SvsLM). These dimensions – which have been termed the "cardinal axes" of color space [2] - are now very widely used to specify and examine the properties of human color vision, and form the axes of the standard physiologically-defined color spaces of MacLeod and Boynton [3] and Derrington, Krauskopf and Lennie [4].

Despite the importance of these axes, few studies attempt to specify the stimulus variations that isolate them for individual observers, and instead assume a "standard observer" based on the average of a large number of individuals. This practice suffices for many applications of color science, but is undesirable when precise calibrations are required, and stands in stark contrast to the standard procedures for calibrating for individual differences in luminance sensitivity [5].

Normal variation in spectral sensitivity can produce individual differences in many aspects of color vision including color matching. These spectral sensitivity variations arise from many physiological factors including individual differences in the relative numbers of the different cones, the spectral peaks and optical density of cone photopigments, as well as differences in macular pigment and lens density [6,7].

Individual variation can also create challenges for accurate color reproduction within and across devices (e.g. monitors, projectors, printers, etc.). Namely, problems could arise if colors produced by one device are not accurately reproduced for a different device *across observers*. For example, modern displays have progressed to feature high dynamic range and wide gamut lighting made possible by utilizing LEDs, OLEDs, and lasers. These technologies use primaries with narrowband spectra, allowing for a larger gamut containing a greater amount of potential colors but could also increase errors in precise color reproduction due to the individual variation across observers [8].

Quantifying individual differences in color vision has been approached in a number of ways. One of these is to directly measure the color matching functions or stimuli of interest (e.g. cone isolating axes) for the observer. A second approach would be to directly measure the sources of variation, for example determining the density of the lens or macular pigments, and then using these to indirectly predict the color matches for the observer. However, both approaches are laborious and often require specialized equipment. Here we explore a third approach, based on direct measurements of luminance sensitivity and applying these to indirectly estimate aspects of chromatic sensitivity. In a previous study [9], we showed that many of the factors affecting luminance sensitivity (e.g. lens and macular pigment density) also impact spectral sensitivity, and thus measurements of luminance sensitivity could be used to predict some of the variations in color matching. Here we extend this logic to specifically examine how well one can estimate an observers' cardinal chromatic axes from their luminance settings. We also extend our previous work by not only modeling but empirically testing these predictions. An advantage of this approach is that equiluminance settings for

individual observers can be and are commonly assessed by a variety of techniques that provide rapid and accurate estimates. These standard techniques include heterochromatic flicker photometry [10,11] and minimum motion [12]. In contrast, as we noted, determining the cardinal chromatic axes is rarely undertaken, and while a number of techniques have been developed to assess individual differences in these axes, they are again time consuming and involve specialized procedures such as the use of auxiliary adapting fields [13-17]. Because of this, there is also relatively poor understanding of how much the cardinal axes potentially vary across color-normal observers, or of the extent to which these variations might impact studies of color processing or perception that are based on nominal estimates of these axes. Thus, a third aim of our work was to characterize the expected degree and pattern of variation in the LvsM and SvsLM axes across individuals.

To address these questions, we first modeled the direction of an individual's cardinal axes predicted by normal variations in optical or photopigment variations, and then compared how these factors jointly affect luminance sensitivity and the cardinal axes. We then sought to validate the model with psychophysical measures of the stimulus directions that isolate an individual's cardinal opponent axes. Results from the model indicate that routinely measured differences in luminance can provide partial (but not complete) information about the cone-opponent directions of an individual observer, though in practice the predicted variations were limited to the SvsLM axis. Exploiting luminance measurements to predict chromatic sensitivity has the advantage of leading to better specification of the color spaces for an individual observer and comes "for free" in

experiments that are already employing standard techniques for specifying luminance sensitivity.

METHODS

Model

We modeled variations in spectral sensitivity (fundamentals) based on estimates of normal variability in the factors affecting the cone fundamentals. Methods for modeling the observers are similar to those methods used in previous studies [7,18,19]. We used Monte Carlo simulations to generate 1000 observers, each varying randomly in known factors that affect luminance and/or spectral sensitivity. These included (1) lens pigment density (sd = 18.7% or 0.3 at 400 nm); (2) macular pigment density (sd = 36.5% or 0.13 at 458 nm); (3) independent variation in the spectral peak (λmax) for each cone (sd = 2.0, 1.5, and 1.3 nm for *L*, *M*, or *S* cones, respectively); (4) independent variation in the optical density of the cone pigments (sd = .09 for *L* and *M*, and .074 for *S*); and (5) independent variation in the LM cone ratios (log change in LM ratio, sd = 0.3). With the exception of LM cone ratios, the values for the standard deviations of the factors were based on Asano et al. (2016)[20]. The standard deviation of the cone ratios was assumed to be a 4-fold change in the ratio based on Carroll, Neitz, & Neitz, 2002 [20]. Each simulated observer was constructed by (1) removing the assumed lens and macular filtering from the Stockman and Sharpe fundamentals; (2) shifting the spectrum along the wavenumber axis to the chosen λmax; (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 [21].

Once an observer was created, we calculated the luminance match, expressed as

angle of tilt of the equiluminant plane in the Derrington-Krauskopf-Lennie (DKL) color

space, relative to the standard observer plane. This space is not standardized, and the

degree of tilt depends on the scaling assumed for the LvsM and SvsLM axes. For our

analyses, we used the following scaling:

```
LMval = 2755 * (Lmb - 0.6568)
Sval = 4088 * (Smb - 0.01825)
LUM = 100 * LUMtest / LUMref
```

Where Lmb, Smb are the MacLeod-Boynton coordinates from which the

coordinates of the nominal white point are subtracted, and the values are then scaled by

factors chosen so that the LvsM and SvsLM units roughly correspond to multiples of

detection threshold [16]. For the current space, an azimuth of 0 degrees corresponds to

the +L direction in the LvsM axis and 90 degrees in azimuth corresponds to the +S

direction in the SvsLM axis. An elevation of zero degrees corresponds to the nominal

equiluminant plane and an elevation of 90 degrees is achromatic/white (CIE 1931

chromaticity of x= .31; y=.316) The luminance was scaled to correspond to 100 times the

Weber contrast of the stimulus, again so that changes in luminance or chromaticity were

roughly equated for multiples of threshold. The calculations estimated the tilt of the

equiluminant plane and the corresponding rotations in the LvsM and SvsLM axes within

the plane in terms of these scaled units, for each observer.

Psychophysics

We implemented two psychophysical experiments to empirically determine the tilt of the equiluminant plane and the location of the opponent axes for a set of observers. A minimum motion paradigm [12] was used for determining individual equiluminant settings/tilt of the equiluminant plane. Participants performed a 2AFC task to judge whether a grating appeared to drift either upward or downward, with the luminance difference within the chromatic grating varied in a staircase. The equiluminance balance was determined by averaging the last 10 of 13 reversals of two interleaved staircases. The stimuli had a nominal mean photometric luminance of 20 cd/m^2 and subtended 2 deg at a viewing distance of 114cm. The patterns were 0.5 c/deg horizontal square-wave gratings and reversed in spatial and temporal quadrature at 2.5 Hz. Settings were made for chromatic gratings defined by two chromaticities that were +/- 80 contrast units along the nominal LvsM or SvsLM axes. The Michelson contrast of the achromatic grating was 10%. Two to four measurements were made for both opponent axes.

A contrast-matching paradigm with selective chromatic adaptation was used to define the cardinal directions. This method is based on the procedure described in Webster et al. (2000)[16]. Chromatic adaptation was implemented using a THOUSLITE LEDCube illuminant falling on a spectrally flat background, producing adaptation at short (peak ~425nm) or long (peak ~635nm) wavelength LEDs to reduce the sensitivity of the S cones or the L and M cones, respectively. Under these conditions perceived contrast should therefore depend primarily on the cones under weaker adaptation. For example, in the presence of the longwave adapting field, stimulus contrasts should mainly

reflect the activity of the S cones. The chromatic direction of the stimulus can then be varied to find the point at which the perceived contrast is highest, and this should correspond to the S-isolating or SvsLM axis. Since a null cannot always be precisely determined, we instead used a comparison task as in Ref. 16 where two different chromatic angles were presented, and the observer judged which contrast was higher. The null should then occur when the pair of directions straddle the SvsLM axis so that their perceived contrast is equal.

Ten healthy volunteers (seven male and three female) aged 24-65 years comprised the observer sample. All participants reported normal or corrected-to-normal acuity and no other inclusion/exclusion criteria were employed. This project was approved by the Institutional Review Board of The University of Nevada, Reno and written informed consent was obtained from each participant. Observers were adapted to either the short or long wavelengths while viewing a stimulus monitor through a beam splitter such that a uniform chromatic field was superimposed over the view of the monitor. For the long wavelength (red) adaptation, the chromaticity coordinates were x=0.69 y=0.30 with a luminance 53 cd/m^2. For the short (blue) wavelength adaptation, the chromaticity coordinates were x=0.16 and y=0.04 with a luminance of 18 cd/m^2. The participants viewed a pair of rectangular patches presented simultaneously, above and below a fixation cross. The colors of the patches were nominally equiluminant and had a contrast of 80 units. They were separated by 10 deg in chromatic angle and were varied during the experiment to "straddle" the opponent axis being tested. The participants judged which of the two stimuli appeared higher in contrast. The mean color of the patches was then

rotated via staircase while maintaining the 10-degree separation until the pair of colors appeared to be the same contrast. The individual's opponent axes were taken as the mean hue angle of the two comparison stimuli at the point of perceived equal or "matching" contrast, determined by the average of the last 10 of 13 reversals of the staircase. Observers repeated the task with both foveal and near-peripheral (4 degrees right and left) fixation, with two to four settings made for each condition. Results reported are based on the mean settings for each observer and condition.

RESULTS

Figure 1 presents the results from both the modeled (simulated) and empirically measured observers to show the relationship between the variations in luminance (x axis) and the cardinal axes (y axis). Specifically, the ordinate gives the degree of rotation within the chromatic plane away from the nominal axis for each cardinal axis (SvsLM or LvsM). The abscissa gives the amount of tilt away from the nominal equiluminant plane. The magnitudes of luminance tilt and chromatic rotation in the SvsLM axis were strongly correlated for the simulated observers (r≈0.86). This correlation was weaker for the actual observers (both fovea and periphery r≈0.57, P=0.06; just fovea r≈0.69, P<0.001) as shown in Figure 1A.

The correlation for tilt and rotation in the LvsM axis was moderate for the simulated (r≈0.77) but not for the behavioral observers (r≈0.28, NS) as shown in Figure 1D. The simulation data also predict that the S axis tilt should weakly correlate (r≈0.55) with the chromatic rotation of the LvsM axis (Figure 1B). However, the behavioral data do not uphold this prediction and are instead poorly correlated (r≈0.24, NS). It can be

seen in Figure 1C that neither the simulation nor the behavioral data show a meaningful correlation between the LvsM axis tilt and the SvsLM axis chromatic rotation (r≈0.08 and r≈0.47 [P=0.03], respectively). The empirically-defined rotations of the LvsM axis were also consistently displaced from the standard observer. We are not sure of the basis for this but a bias in the same direction was found in previous studies using different variants of the isolation method with different observers and hardware [16].

Figure 2 represents the correlations for tilt and rotation for each axis in the behavioral data – but split between foveal and peripheral conditions. In the foveal condition, the SvsLM axis shows a moderate correlation (r≈0.69, P<0.05) while the LvsM axis was uncorrelated (r≈0.01, NS). However, in the peripheral condition the LvsM axis was moderately correlated (r≈0.68 P<0.05) while the SvsLM axis showed a weak correlation (r≈0.44, NS).

Note that the strength of the relationship between the tilt and rotation may be underestimated from the linear correlation if the relationship is instead nonlinear (as evident in Figure 1D for LvsM tilt vs. rotation). Moreover, for these linear correlations, we treated the tilt of the equiluminant plane as a separate parameter along each axis (i.e. as the tilt of SvsLM axis or the tilt of the LvsM axis). However, the tilt of the plane in color space requires two parameters (angles, here) in addition to the fixed white point, for a unique determination. If the information provided by the two different axes is perfectly correlated, the information would be redundant and only one tilt measure would be needed. A similar situation exists regarding the location of the chromatic axes. If the variation in the locations of the LvsM and SvsLM chromatic axes within the

equiluminant plane are highly correlated, then the tilt of the equiluminant plane could predict the rotation of both axes. If, however, the LvsM and SvsLM parameters for the rotations and equiluminant tilts are independent of each other, then measuring the luminance tilts of both axes would provide additional information that should better predict the rotations of each axis.

Figures 3 and 4 show the predicted and observed relationships between the luminance tilts along either axis (Figure 3) and the rotations within the chromatic plane (Figure 4). The model predicts minimal correlation ($r \approx 0.26$) between the tilts along either axis, as also found for the behavioral data ($r \approx 0.09$, NS). For the rotations of the two cardinal axes, the model this time predicts a weak correlation ($r \approx 0.45$) while the behavioral data are again uncorrelated ($r \approx 0.08$, NS)

Because, the LvsM and SvsLM rotations and tilts are not highly correlated, then the combined information from the two axis tilts should better predict both rotations and thus more completely specify an individual's color space. Consequently, we combined the information from the two axis tilts to examine how much, if at all, the predictions of the hue axes were improved. Table 1 shows the single parameter correlations from Figures 1 and 3 (upper panels) as well as a multiple-correlations using both LvsM and SvsLM axis tilts simultaneously to predict the rotation of each of the hue axes (lower panels).

The multiple-correlations results for the model do not show significant improvement in the ability to predict the location of both the SvsLM ($r \approx 0.87$ vs. 0.86 for S tilt alone) but predict a modest improvement for the LvsM values ($r \approx 0.85$ vs. 0.24

alone). Similarly, the behavioral correlations are improved for the SvsLM rotation although the correlation for the LvsM axis remains weak. Specifically, using the tilts along both axes to predict the rotations accounted for $r^2 \approx 0.42$ and $r^2 \approx 0.06$ percent of the variance in the rotations for SvsLM and LvsM hue axis, respectively.

As noted, variations in luminance and spectral sensitivity arise from many factors. As a final question we explore the relative contribution of each of these to the tilts and rotations in the plane. For these analyses only one factor was varied at a time while the remaining were fixed at the standard observer. Table 2 show the magnitude of the luminance tilts or chromatic rotations for each variable. For luminance the strongest contribution to the variations are cone ratios (sd=1.96) for LvsM and macular pigment (sd=0.68) for SvsLM. For the chromatic axes the strongest contribution to the variations are macular pigment (sd=2.71) and lens density (sd=0.95) for SvsLM, and cone ratios (sd=1.04) for LvsM. They also show that in general the predicted rotations in the cardinal axes are larger than the individual differences in the tilts defining luminance sensitivity.

DISCUSSION

In a previous study we showed that luminance settings can be used to partially predict and thus reduce errors in individual color matching functions, because the luminance and spectral sensitivities are affected by common factors [9]. Here we have extended this work to show that equiluminance settings can also lead to specific improvements in the specification of the cardinal chromatic axes defining color coding. While improvements to the technique and algorithm itself could lead to more accurate predictions, our goal was to show in principle that significant improvement over the

standard observer (which is commonly assumed for the cardinal axes) is already potentially available to any study that is already correcting for an individual's equiluminant settings, a procedure that has itself become common place. The present results suggest that the SvsLM axis can be more accurately characterized for an individual simply from the observer's luminance sensitivity. While a number of techniques have been described for empirically specifying the cardinal axes [17] our procedure again has the potential to improve the estimate of the SvsLM and LvsM line without requiring a separate procedure.

The predictions were partially corroborated in direct measurements of the luminance tilts and chromatic axis rotations, though the empirical measurements did not reveal a significant effect for predicting the LvsM axis rotation. Also, we showed that the predictive capacity is improved if the equiluminant settings along two axes are used in the prediction. As also noted, we only evaluated the simple linear correlations between the variables. In actual practice the predictions could be substantially improved by incorporating the nonlinearities in the relationships between the luminance and chromatic angle changes as evident in Figure 1 for the LvsM axis.

There are several explanations as to why the behavioral measurements did not perform as well as the model. One is that as pointed out in the introduction, measurements of the cardinal axis directions are harder to obtain than equiluminance settings – which by comparison are highly sensitive - and the variability may have introduced errors in estimation of the axis locations, resulting in a lower correlation. Nevertheless, even these partial predictions represent an improvement over reliance on

the standard observer, and again can be exploited through existing measurements of

luminance which are well established and easy to implement on common display devices.

ACKNOWLEDGMENTS

REFERENCES

1. B. B. Lee, "Color coding in the primate visual pathway: a historical view," J. Opt. Soc. Am. A 31, A103–A112 (2014).
2. J. Krauskopf, D. R. Williams, and D. W. Heeley, "Cardinal directions of color space," Vision Res. 22, 1123–1131 (1982).
3. MacLeod, D. I., & Boynton, R. M. (1979). Chromaticity diagram showing cone excitation by stimuli of equal luminance. *JOSA*, *69*(8), 1183-1186.
4. Derrington, A. M., Krauskopf, J., & Lennie, P. (1984). Chromatic mechanisms in lateral geniculate nucleus of macaque. *The Journal of physiology*, *357*(1), 241-265.
5. Lennie, P., Pokorny, J., & Smith, V. C. (1993). Luminance. *JOSA A*, *10*(6), 1283-1293
6. Webster, M. A., & MacLeod, D. I. (1988). Factors underlying individual differences in the color matches of normal observers. *JOSA A*, *5*(10), 1722-1735.
7. Asano, Y., Fairchild, M. D., & Blondé, L. (2016). Individual colorimetric observer model. *PloS one*, *11*(2), e0145671.
8. Smet, K. A., Webster, M. A., & Whitehead, L. A. (2022). Using smooth metamers to estimate color appearance metrics for diverse color-normal observers. *Color Research & Application*, *47*(3), 555-564.
9. Lee, K.R., Richardson, A.J., Walowit, Eric, Crognale M.A., Webster M.A. (2020). Predicting color matches from luminance matches. J. Opt. Soc. Am. A 37, A35-A43.
10. Rood, O.N., "On a photometric method which is independent of color" American Journal of Science Sep 1893, s3-46 (273) 173-176; DOI: 10.2475/ajs.s3-46.273.173
11. R. A. Bone and J. T. Landrum, "Heterochromatic flicker photometry," Arch. Biochem. Biophys. 430, 137–142 (2004).
12. 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).
13. Tansley, B. W., & Boynton, R. M. (1976). A line, not a space, represents visual distinctness of borders formed by different colors. Science, 191(4230), 954-957.
14. Webster, M. A., De Valois, K. K., & Switkes, E. (1990). Orientation and spatial-frequency discrimination for luminance and chromatic gratings. Josa a, 7(6), 1034-1049.
15. Webster, M. A., & Mollon, J. D. (1994). The influence of contrast adaptation on color appearance. Vision research, 34(15), 1993-2020.
16. Webster, M. A., Miyahara, E., Malkoc, G., & Raker, V. E. (2000). Variations in normal color vision. I. Cone-opponent axes. JOSA A, 17(9), 1535-1544.
17. Smithson, H. E., Sumner, P., & Mollon, J. D. (2003). How to find a tritan line. Normal and defective colour vision, 279-287.

18. Smith, V. C., Pokorny, J., & Starr, S. J. (1976). Variability of color mixture data—I. Interobserver variability in the unit coordinates. *Vision Research*, *16*(10), 1087-1094.
19. Webster, M. A., Miyahara, E., Malkoc, G., & Raker, V. E. (2000). Variations in normal color vision. II. Unique hues. *JOSA A*, *17*(9), 1545-1555.
20. Joseph Carroll, Jay Neitz, Maureen Neitz; Estimates of L:M cone ratio from ERG flicker photometry and genetics. *Journal of Vision* 2002;2(8):1.
21. 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 Aug;39(17):2901-27. doi: 10.1016/s0042-6989(98)00225-9. PMID: 10492818.