Forward: Abstract & Purpose

We have discovered dramatic, between-observer differences in the interaction effects of hue and spatial frequency (SF) on equiluminance settings derived from the minimum motion method. As described below, the pattern of our results suggests that the form of interaction obtained for a given of observer may reflect that observer's l:m cone ratio. If this speculation is confirmed, the tests we have developed could provide a simple, psychophysical method for estimating l:m cone ratios. For this reason we would love to image the retinas of several of our observers.

In our procedure, equiluminant settings are estimated separately for a saturated red and green to a fixed neutral gray using the minimum motion method with an annular, square-wave grating stimulus. Estimates for each color condition are made using 5 and 10 cycle/deg square wave gratings (our low-SF and high-SF conditions). Observers fall on a continuum between two extreme data patterns: in one extreme, for L_{low} and L_{high}, the photometric luminances of the equiluminant green settings obtained in the low-SF and high-SF conditions, $diff_{green} = L_{Low}-L_{High}$, is strongly negative. In the other extreme, $diff_{green}$ is strongly positive. Most strikingly, whichever pattern an observer produces for green is likely to reverse for red: e.g., an observer producing a negative $diff_{green}$ tends to produce a positive $diff_{red}$ of a similar magnitude. Likewise, a $+diff_{green}$ predicts a $-diff_{red}$. The results for all observers (N=20) fall on a linear locus between these extremes ($r = -.9$, $p < .0001$).

Synopsis: Individual Differences in Perceived Equiluminance

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The minimum motion method for obtaining individuals' perceptually equiluminant display settings between hues is a standard tool used by psychophysicists (Anstis & Cavanagh 1983). The logic of the minimum motion method is as follows: two sets of alternating square wave gratings sequentially presented stepping ¼ step per frame will create the percept of motion. An example sequence is depicted in Fig. (1). The four gratings in Fig. (1b) and Fig. (1c) show how the gratings in the current studies are mapped onto an annulus. In the experiment described below, the stimulus was displayed on a background gray with RGB display settings of [100 100 100]. These were also the settings used for the **N**eutral gray patches of the annular gratings presented in the 1st and 3rd frames with the **G**reen patches. The luminance of the **G**reen patches is varied across trials by increasing or decreasing the component red- and blue-guns for a fixed green-gun setting. The grays that define the monochromatic annular grating presented in the 2nd and 4th frames are slightly **L**ighter and **D**arker than the **N**eutral gray. This paradigm is based on the assumption that the motion elicited by an apparent motion stimulus is detected by a single mechanism sensitive to luminance-defined motion. It follows that when the **G**reen patches are equiluminant to the **N**eutral gray, the effective input to the motion system consists of a homogeneous field of mean luminance alternating with an annular square wave grating that reverses contrast each time it appears. This stimulus should yield ambiguous motion. Fig. (1b) and Fig. (1c) show the possible perceptual outcomes when the **G**reen and **N**eutral gray patches do not appear to be equiluminant. Though the patches in these figures are created using the same display settings, if the **G**reens appear higher in luminance than the **N**eutral gray, then they should, as in the case diagrammed in Fig. (1b) generate counterclockwise motion by lining up with the **L**ight patches in the alternate frames, whereas if the **G**reen patches appear lower in luminance than the **N**eutral gray as in Fig. (1c), they should generate clockwise motion by lining up with the **D**ark patches in the alternate frames.

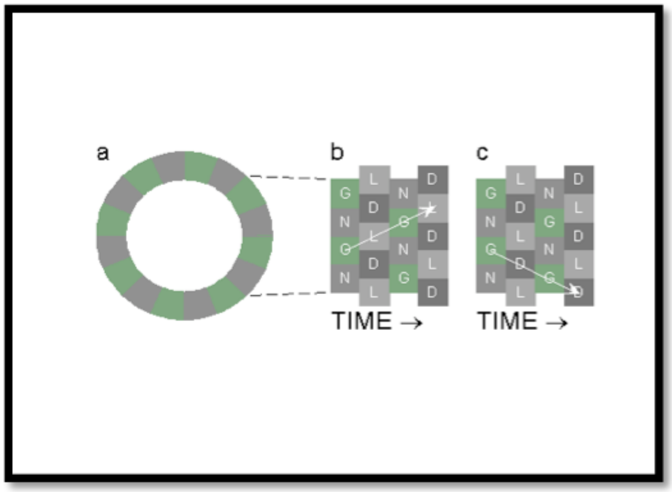

Figure 1

For a given value G of the green-gun, our goal is to find the value A_{ambig} such that the light produced by setting the red and blue guns to A_{ambig} and the green gun to G yields ambiguous motion when assigned to the green patches of the motion stimulus shown in Fig. (1). Fig. (2), the relevance of which will be discussed in more detail later, shows cumulative Gaussian functions fitted to Participant (P)1's psychometric data. In this case, the green-gun value was fixed at 114, and the yoked red- and blue-gun value **A** was varied (using a method of constant stimuli) and is plotted on the abscissa. The participant judges whether the stimulus motion was clockwise or counterclockwise, and we record whether the participant's response signals that the **G**reen patches line up with the **L**ight components of the square wave or with the **D**ark components. As the A-value increases along the abscissa, so does the probability of a match in the **L**ight direction, plotted along the ordinate. A_{ambig} is estimated as the A-value associated with a participant's 50% probability of a **L**ight match, the point where the function crosses through the blue line plotted on the graph. In the case of the large-dashed function, A_{ambig} for this participant is estimated to be 31. The steepness of the functions and the tightness of the confidence intervals indicate that our apparent motion stimuli yields ambiguous motion in a very small range of A-values for a given green-gun value.

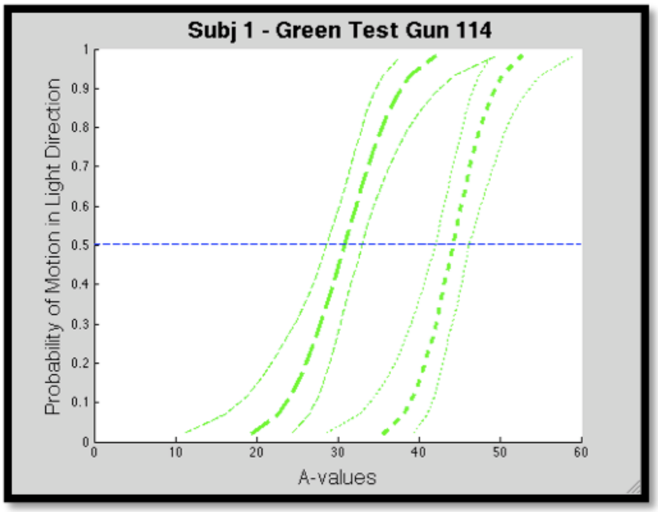

Figure 2

Typically we estimate A_{ambig} for several levels of green saturation and fit a quadratic function to the range of green-gun values. The functions represented by the dashed and dotted lines in Fig. (3) show two typical functions fitted to A_{ambig} points marked by four circles along each curve. A green-gun increase, plotted along the abscissa, indicates a more saturated green, the increased brightness of which is balanced by a decrease in A_{ambig} plotted along the ordinate. This function allows us to select any set of green-gun values within the range and, using the function produced by each participant, interpolate the associated A_{ambig} values. Using these display settings, we can present stimuli that are perceptually equiluminant to individual participants. Note that the steepness of these functions increases with higher G values.

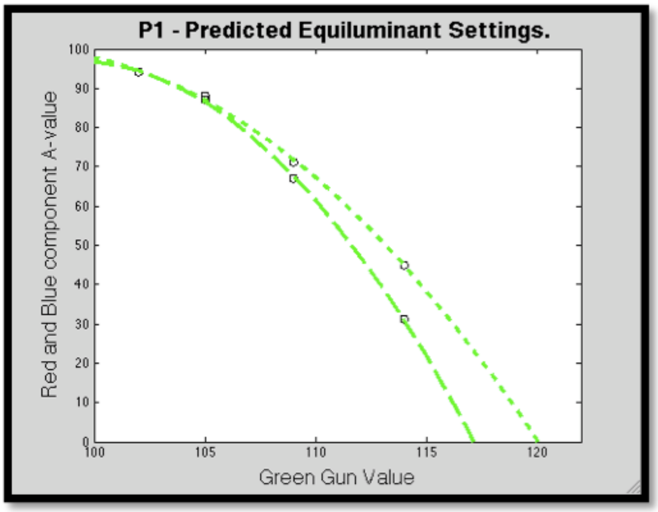

Figure 3

Previously, we believed that the variations in individuals' display settings were merely small, but significant, variations from a mean centered near photometric equiluminance due in totality to individual variation in perceived luminance of hues.

Seemingly contradicting the logic of the minimum motion paradigm, we have now found that the setting for a given hue depends strongly on the spatial frequency of the motion stimulus used in the minimum motion calibration display. P1 produced both functions in Fig. (2). The dashed function was produced using a 5 cycles/deg. annular square wave. The dotted function was produced using a 10 cycles/deg. annular square wave. The entire annulus subtended .03 deg. of visual angle. At a set green-gun value, in the low- spatial frequency display, A_{ambig} is 31, whereas in the high- spatial frequency display A_{ambig} is significantly higher at about 45. We define the size of a threshold shift as an observer's A_{ambig} value in the low- spatial frequency condition minus the A_{ambig} value in the high-spatial frequency condition. In this case where the green-gun is set to 114, a relatively high saturation setting, P1's green difference is -14. This higher threshold in the high- spatial frequency condition suggests that the increase in spatial frequency causes the **G**reen to be perceptually darker than the **G**reen in the lower spatial frequency display. In the context of the low- spatial frequency motion display, green-gun quanta seem to be relatively more effective than red-or-blue-gun quanta at increasing brightness (at least for the mechanism sensing the motion of this stimulus) than they are in the high- spatial frequency display.

The A_{ambig} values from Fig. (2) also appear as data points in Fig. (3); they are the circles corresponding to the 114 green-gun level on the dashed and dotted functions for the low- and high- spatial frequency conditions, respectively. The other data points are estimated A_{ambig} values corresponding to other (lower) green-gun levels. Both functions cross the x-axis at the green-gun level that, when displayed alone – i.e., with the red and blue guns turned off – is predicted to be perceptually equiluminant to the **N**eutral gray. Any green-gun setting above this point, with or without a combined A-value, will produce unambiguous motion in the **L**ight direction. The two functions do not cross the x-axis at the same point, illustrating that while the display settings, and hence the photometric luminance, of the **G**reen patches in both the low- and high- spatial frequency displays is the same, their perceived luminance is not.

The functions in Fig. (3) lie on top of each other where they correspond to the lowest green-gun values. The largest spatial-frequency-driven difference between participants' A_{ambig} points is at the point where the steepest function crosses the x-axis. However, as the green-gun levels increase and the A-values approach 0, making a reliable estimation is difficult since we cannot lower the guns below 0. To exploit the difference found for the highest levels of saturation, A_{ambig} values were estimated at the most saturated green-gun level for which each participant could produce a reliable A_{ambig} value in both conditions. The range of green-gun settings in which this is possible varies between participants, so the maximum of this green range was determined through piloting. In most cases A_{ambig} could still be estimated for A values as low as 20-40, so we shifted the saturation until the A values were near 20-40 in the condition with the steeper slope.

While looking for temporal frequency effects in a previous experiment, we found that while all participants showed a threshold shift, some produced a negative green difference, while others produced a positive one. Wanting to explore whether this effect remained constant if we tested with a different hue, participants' red ranges were also determined through piloting in the same manner as described for greens. Participants were then tested in four conditions in Experiment 2: 1) Low- Spatial Frequency – Green, (2) High- Spatial Frequency – Green, 3) Low- Spatial Frequency – Red, (4) High- Spatial Frequency – Red. Fig. (4) shows the P1's green data from Fig. (2) in addition to cumulative Gaussian functions fitted to her red data. Like the functions for the green data, the red data functions are dashed for the low- spatial frequency display and dotted for the high spatial frequency display. In her case, the relative relationship of the low- and high- spatial frequency functions has reversed between hues. The increase in spatial frequency causes the red color component to be perceptually lighter than the red in the lower spatial frequency display. P1's red difference is <u>24</u> and her green difference is -<u>14</u>.

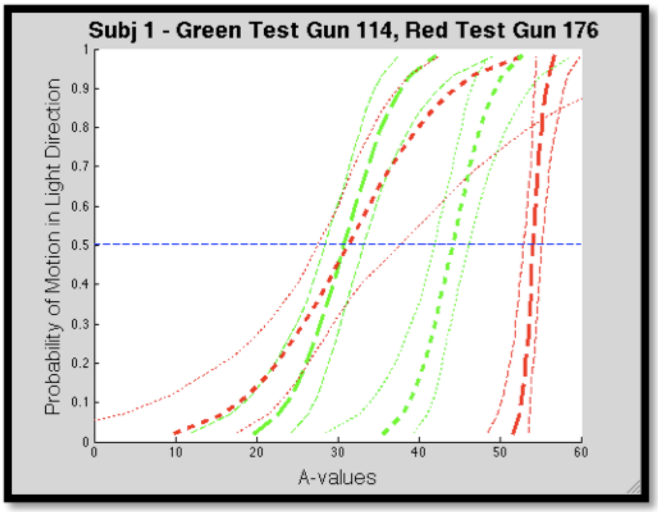

Figure 4

After collecting data for 7 participants, all 7 showed an interaction effect between hue and spatial frequency. 4 of these participants matched P1's pattern of functional relationships, shown in Fig. (4). The other 3 showed the opposite pattern of functional relationships. P2 is a typical participant of this type whose data are documented in Fig. (5). For P2, in contrast to P1, an increase in spatial frequency causes the green color component to be perceptually lighter than the green in the lower spatial frequency display and the red color component to be perceptually darker than the red in the lower spatial frequency display. P2's red difference is <u>-16</u> and his green difference is <u>20.</u>

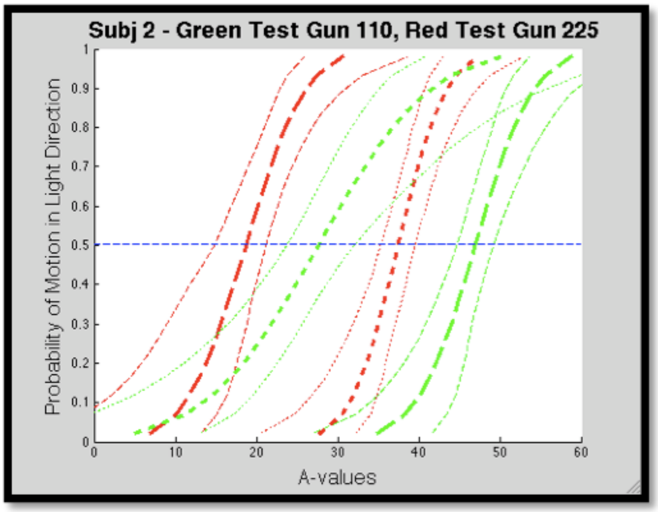

Figure 5

Elaborate psychophysical methods have been designed in an effort to behaviorally estimate an individuals’ ratio of long- to medium-wavelength cones. We did not construct our experimental paradigm in an attempt to do so, but it seems plausible that the strong correlation between the red and green differences across participants could be explained by differences in their relative l:m cone ratios. The lights used in our stimuli differentially activate the l- and m- cone classes. Suppose a participant has more l- than m-cones. Then her cone mosaic might be expected to sample long-wavelength light with higher acuity than medium-wavelength light. This leads us to speculate, regarding our apparent motion paradigm; this hypothetical participant, in comparison to the low-spatial frequency display, may be relatively more sensitive to long-wavelength quanta than to medium-wavelength quanta in the high-spatial frequency display. This explanation would predict that P1 has a high l:m cone ratio and P2 has a low l:m cone ratio. P1’s higher threshold in the green high-spatial frequency versus the green low- spatial frequency condition indicates that the physical quanta of the green, as perceived by the her sparser m-cones, does not drive as strong of a brightness percept when the visual information is displayed at higher spatial frequencies. Consequently, P1’s more densely distributed l-cones do much better at driving a strong brightness percept from the red quanta displayed at higher spatial frequencies. The converse is true for P2. P2’s sparser l-cone samples of the red quanta in the high-spatial frequency condition does not drive as bright a percept as such in the low- spatial frequency display. P2’s more densely distributed m-cones do much better at perceiving brightness via green quanta displayed at higher spatial frequencies.

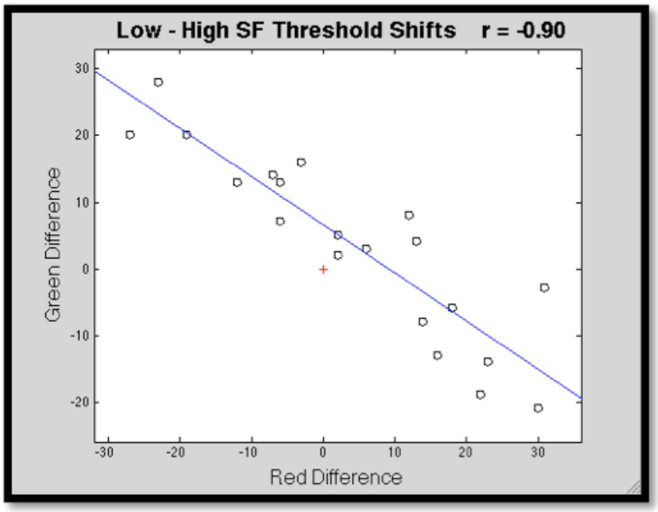

Figure 6

Fig. (6) shows the result when we expanded this data set to 20 participants. In this figure, the green difference is plotted against the red difference for each participant. There is a highly significant negative correlation. Participants plotted more centrally have pairs of smaller differences, and as the differences increase the distribution stretches along a clearly defined continuum in which larger green or (red) differences are coupled with larger red or (green) differences. The regression line is shifted toward a positive red and green difference from the origin. This supports the argument that when fewer cones are responding to the stimulus, encoding information from the high- spatial frequency display is less effectual. The participants that do not match one of the patterns depicted in Fig. (4) or Fig. (5) lie in the center of the distribution, both differences taking small positive values. Following the logic of this cone ratio argument these participants are likely to have a more balanced l:m ratio. For both colors of the display these participants can sample effectively enough to extract the extra information the high- spatial frequency display carries.

We would like to, for several participants spread across this distribution, obtain their retinal images to evaluate our prediction as well as evaluate how other variables such as evenness of distribution of the sparser cone class may fit into our model. There are many variations to the current experiment that can further elucidate other aspects of low level visual processing. The ease with which participants can be evaluated using these paradigms has the potential to provide researchers with an easy means of estimating relative distributions of cone classes.