Interactions of chromaticity and luminance in edge identification depend on chromaticity

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Abstract
The goal of this work was to study interactions of chromaticity and luminance in edge identification. Two horizontal spatial sawtooth patterns, one with positive and the other with negative harmonics, were compared in a two-alternative forced-choice (2-AFC) procedure. The observer identified which pattern had sharp upper or lower edges. The fundamental frequency was 2 cycles/deg (cpd), with 5 cycles presented in a 2.5-deg square field. The pattern was presented as a 1-s raised temporal cosine, replacing part of an 8-deg background. Stimuli were specified in a cone troland \((l, s, Y)\) chromaticity space, with correction for individual equiluminance at a nominal 115 td, and individual tritan direction. A preliminary set of interleaved staircases established edge identification for the six directions of the \((l, s, Y)\) space. Three compound stimuli combining two orthogonal directions were chosen and included with the end-points in five randomly interleaved staircases. For combinations of \(Y\) with \(l-\)chromaticity, or \(l-\) with \(s-\)chromaticity, probability summation was observed. Combinations of \(Y\) with \(s-\)chromaticity revealed opponency. Data for \(1_s, 1_y\) and \(2_s, 2_y\) were subadditive; data for \(1_s, 2_y\) and \(2_s, 1_y\) were additive. Control studies using detection rather than edge identification revealed probability summation for all combinations. Luminance edges did not enhance stimuli with \(l-\)chromaticities. There was an interaction of luminance edges with \(s-\)chromaticities. Dim “blues” and bright “yellows” showed linear summation. Bright “blues” and dim “yellows” showed opponency.

Keywords: Edge identification, Chromaticity, Luminance

Introduction
Early studies of color vision used optical systems with simple spatial displays, usually circular fields in a surround. The major stimulus variables were narrowband spectral stimuli (Wright, 1946), reviewed in Pokorny and Smith (1986). A few studies found ways to study chromaticity-luminance interactions using optical systems (Cole et al., 1993; Chaparro et al., 1994). The advent of monitor systems allowed not only the use of complex spatial stimuli but also stimuli that varied only in chromaticity at equiluminance, varied only in luminance at a chromaticity metameric to equal energy white, or provided a combination of the two. While many studies concentrated on discrimination of equiluminant stimuli (Mullen, 1985; Krauskopf & Gegenfurtner, 1992; Zaidi et al., 1992; Mullen & Losada, 1994), interest turned also to chromaticity-luminance interaction (Mullen et al., 1997; Mullen & Sankeralli, 1999) and chromaticity interactions between color pathways (Mullen & Sankeralli, 1999). The term “interaction” refers to the threshold sensitivity to stimuli that contain two components, for example, luminance plus chromaticity of one color pathway or two chromaticities from two color pathways.

The results of studies of chromaticity-luminance interactions are equivocal, some found stochastic independence in detection of stimuli exciting long (L-) and middle (M-) wavelength-sensitive cones (Mullen et al., 1997; Mullen & Sankeralli, 1999) while others (Gur & Akri, 1992; Gur & Syrkin, 1993; Syrkin & Gur, 1997) reported linear summation. The discrepancy is not resolved, but Syrkin and Gur (1997) suggested that linear threshold summation of chromatic and luminant components might be a feature of suprathreshold tasks. A study of chromaticity-luminance interactions for short (S-) wavelength-sensitive cone stimuli and a study of equiluminant chromatic axis interaction similarly revealed stochastic independence (Mullen et al., 1997; Mullen & Sankeralli, 1999).

Modern electrophysiology has revealed three primary processing streams from retina to the lateral geniculate nucleus (LGN). These are the magnocellular (MC-) pathway, summing L- and M-cone signals, and processing achromatic contrast information, the parvocellular pathway (PC-), a spectral opponent system differenting L- and M-cone signals, and a portion of the koniocellular (KC-) pathway dominated by S-cone signals. The MC-pathway is often considered to be the substrate of a psychophysical (L + M) “luminance” pathway (Lee et al., 1988); the PC-pathway is con-
sidered the substrate for the psychophysical L–M spectral opponent pathways and the KC-pathway is considered the substrate for the psychophysical S-cone spectral pathway (Lee et al., 1993). Based on knowledge of the three retinal pathways, we can develop hypotheses about chromaticity-luminance interactions in tasks that tend to be determined by early retinal pathway signals. (1) If the stimulus favors activity in MC-pathway by using a transient onset stimulus, we might expect independence of the luminance (MC-pathway excitation) and both spectral opponent (PC- and KC-) pathways. (2) If the stimulus has a graded onset, MC-pathway sensitivity to achromatic stimuli is lower than the PC-pathway sensitivity (Leonova et al., 2003; Smith & Pokorny, 2003). Leonova et al. (2003) found that a 1-s raised temporal cosine presentation of a D6 stimulus gave a spatial contrast sensitivity function characteristic of the PC-pathway. Consider chromaticity-luminance summation within the PC-pathway. We might expect edge enhancement of a color border by adding luminance. There are four subclasses of PC-pathway cell, characterized by their preferred chromaticity and luminance directions. A (+L–M) prefers a reddish chromaticity and/or luminance increment; a (–L+M) prefers a reddish chromaticity and/or a luminance decrement; a (+M–L) prefers a greenish chromaticity and/or luminance increment; a (–M+L) prefers a greenish chromaticity and/or a luminance decrement. Further, the cell responses are rectified by the spike generation mechanism. Thus, monopolar stimuli (e.g. bright red-dim white) will tend to favor only one subclass (+L–M) of the PC-pathway retinal ganglion cells. PC-pathway retinal ganglion cells show edge enhancement for achromatic stimuli but not for equiluminant color stimuli (Ingling & Drum, 1973; Lee et al., 1998). The monopolar stimulus combines the appropriate chromatic with the appropriate achromatic stimulus to produce some edge enhancement in a given cell type. We expect independence when combining the achromatic PC- and the KC-pathway excitation. (3) Stimuli combining chromatic PC- and KC-pathway signals should show independence provided edge identification is determined by the retinal signals.

The goal of the current work was to study interactions of chromaticity and luminance in a suprathreshold task using monopolar stimuli. We used edge identification of a spatial sawtooth stimulus and presented the sawtooth stimuli with a slow temporal onset and offset to render the MC-pathway input insensitive (Leonova et al., 2003).

Materials and methods

Equipment

The experimental display was generated on a calibrated color monitor system (Smith et al., 2000). Stimuli were specified in a relative cone troland (l, s, Y) chromaticity space (Smith & Pokorny, 1996), with correction for individual equiluminance at a nominal 115 td, and individual tritan direction. In this space, the l-direction represents an exchange of L- and M-cone excitation at equal luminance with the L- and M-cones normalized to luminance (L + M = Y). The s-direction is the S-cone excitation normalized to Y at the white point. Y represents the trolands calculated for the Judd (1951) observer. For the purposes of data display and analysis, we normalized the chromaticity diagram at equal energy white. Thus, the chromaticity space is a contrast space (l–l_w, s–s_w, y–1).

Two horizontal spatial sawtooth patterns, one with positive and one with negative harmonics were used (Fig. 1). Five cycles at a fundamental frequency of 2 cpd were presented. The stimuli could be presented either in temporal or in spatial forced choice. For temporal forced choice, the patterns extended a 2.5-deg square and were viewed foveally. For spatial forced choice, the patterns extended 1.25 deg × 2.5 deg, separated by 0.5 deg. A fixation cross

Fig. 1. Examples of the stimuli. On the left is shown a sawtooth pattern with sharp upper edges (positive harmonics); on the right is a sawtooth pattern with sharp lower edges (negative harmonics).
Chromaticity-luminance interactions

Procedure

Measurements were made following a 2-min adaptation to the surround and fixation. Removal of the fixation point signaled the beginning of a trial. For temporal forced choice, the patterns were presented in two intervals with random interval order. At the end of the trial, the observers signaled whether the sharp upper edges were in interval (1) or interval (2). For spatial forced choice, the patterns were presented simultaneously with random left/right order. The observers signaled whether the sharp upper edges were on the left or on the right. For the detection criterion, the trial contained either the pattern or the blank screen. The observer’s task was to identify the temporal or spatial interval containing the pattern.

In a preliminary series, thresholds were established for the six directions of the \((l - l_w, s - s_w, y - 1)\) color space. Based on these measurements, three intermediate directions, defined in threshold units, were chosen for each pair of orthogonal directions. The three compound stimuli were then included with the orthogonal directions in five randomly interleaved staircases, using a 3-correct/1-incorrect reversal rule. The stimulus contrast for the initial trials was easily identifiable. The contrast was then reduced to a criterion level and ten reversals were obtained in a 20-min session. Twelve sessions were needed to complete data for all six directions. Three replications were obtained for each pair of directions. The data were expressed in cone trolands contrast units \((l - l_w, s - s_w, y - 1)\) as mentioned above.

Observers

Three observers (including author VCS) participated. All were female with normal visual acuity (with correction) and normal color vision. Color vision was assessed using the Ishihara and Standard Pseudo Isochromatic Plate tests and the Neitz OT anomaloscope. The observers showed superior discrimination on the Farnsworth-Munsell 100 hue test (total errors < 40).

Results

Fig. 2 shows data for temporal forced choice and the combination of \(l\)-chromaticity \((l - l_w)\) and luminance contrast \((y - 1)\) for two observers (VCS & IY). The plot frame represents one plane of the chromaticity contrast space normalized to white. Here we use color names for the dominant percept associated with the stimulus to orient the reader. The data combine four separate conditions, bright and dim “reds” with bright and dim “greens”. On the horizontal axis “reddish” is positive and “greenish” is negative; on the vertical axis bright is positive and dim is negative. The center of the plot is the 115 td “white”. The solid squares show edge identification; the circles show detection. For pure luminance contrast (vertical through origin), detection of the chromaticity pattern was much more sensitive than edge identification. For equiluminant chromatic contrast (horizontal through origin), detection was much more sensitive than edge identification.

We fit the data according to previous literature studies of chromaticity-luminance summation (Mullen et al., 1997; Mullen & Sankeralli, 1999). The fits use the Quick pooling formula

\[
l = \left[ \left( \frac{x}{x_{th}} \right)^k + \left( \frac{y}{y_{th}} \right)^k \right]^{1/k},
\]

where \(x_{th}\) and \(y_{th}\) are the thresholds on the major axes and \(k\) is an exponent representing the probability summation. A power of unity represents linear summation, a power of 2 represents vector summation, and higher powers represent increasing numbers of stochastic channels. The four quadrants were fit simultaneously giving 20 data points for three free parameters. The values of \(k\) were 2.21 (detection) and 1.62 (edge identification) for VCS and 2.79 (detection) and 1.96 (edge identification) for IY.

Mullen et al. (1997) and Mullen and Sankeralli (1999) reported \(k\) values of 3.5 ± 1.30 for their observers. Our values are a little lower but do show overlap. Our experiment used monopolar axes (e.g. red with light, green with dark) rather than bipolar axes (e.g. red–green combined with light–dark). The monopolar axes will excite only one subclass of four PC-pathway subclasses while the bipolar axes will excite two subclasses of PC-pathway subclasses. Thus, the monopolar stimuli may have restricted the number of higher order channels. Our data agree with studies showing probability summation (Mullen et al., 1997; Mullen & Sankeralli, 1999). They do not agree with studies showing linear summation (Gur & Akri, 1992; Gur & Syrkin 1993; Syrkin & Gur, 1997), despite the adoption of a suprathreshold task."
Fig. 3 shows data for temporal forced choice and the combination of \( s \)-chromaticity (\( s-s_w \)) and luminance contrast (\( y-1 \)) for the same observers. The plot frame is similar to that of Fig. 2 but now combining “violet” [positive (\( s-s_w \))] and “yellow” [negative (\( s-s_w \))] with luminance contrast. As for \( l \)-chromaticities, observers were much more sensitive to \( s \)-chromaticity detection than edge identification. The detection data are fit by probability summation [eqn. (1)] with powers for \( k \) of 1.73 and 1.41 for VCS and IY, respectively. Again these values were somewhat lower than noted by Mullen and Sankeralli (1999) who reported 2.63 ± 0.66 for the S-cone and luminance axes. The edge-identification data could not be fit by the probability square. Very high contrasts were needed for combinations of “bright violet” and “dark yellow.” In comparison, “dark violet” and “bright yellow” combined almost linearly. We fit these data by a vector summation model:

\[
1 = \left( \frac{x}{x_0} \right)^2 + \left( \frac{y}{y_0} \right)^2 + 2 \left[ \left( \frac{x}{x_0} \right) \left( \frac{y}{y_0} \right) \cos(\alpha) \right]^{0.5},
\]

where \( x_0 \) and \( y_0 \) are the thresholds on the major axes and \( \alpha \) is the angle of vector summation. An angle of 0 deg represents linear summation, comparable to a \( k \) of 1 in eqn. (1); an angle of 90 deg represents vector summation of orthogonal components and is comparable to a \( k \) of 2 in eqn. (1); and angles near 180 deg represent opponent cancellation. The four quadrants were fit simultaneously giving 20 data points for three free parameters. The fits gave angles of 148 deg and 147 deg for observers VCS and IY, respectively.

Fig. 4 shows data for temporal forced choice and the combination of \( l \)-chromaticity and \( s \)-chromaticity for the same observers. This plane (\( l-l_w, s-s_w \)) is a pure chromaticity plane with approximate hue percepts “purple” in the upper right, “orange” in the lower right, “yellow–green” in the lower left, and “blue–green” in the upper left. The data for both detection and edge identification can be fit by probability summation with powers of \( k \) of 2.08 (detection) and 3.53 (edge identification) for VCS and powers of 3.43 (detection) and 1.77 (edge identification) for IY, respectively. These powers were more variable than the values of 2.25 ± 0.22 noted by Mullen and Sankeralli (1997); however, the data were noisy. There was a suggestion that the identification data showed asymmetry and might be better fit by the vector model. However, significantly improved fits were not obtained and the vector angles were not easily interpretable. Additionally, the observers veered in opposite directions, suggesting that the noisiness of the data was the predominant factor.

The data of Fig. 3 for the \( s \)-chromaticity direction were unexpected. To check the validity of these data, we adopted a spatial forced-choice paradigm to see if the result would be replicated in a slightly different viewing situation. Fig. 5 shows the data for LJ collected using spatial forced choice. The top panel shows the results for \( l \)-chromaticity and luminance, the middle panel shows the results for \( s \)-chromaticity and luminance, and the bottom panel shows the results for \( l \)-chromaticity and \( s \)-chromaticity. The data gave a reasonable replication of the temporal forced-choice data. One difference was that detection and edge identification were similar.

Fig. 3. Temporal forced-choice data for the combination of \( s \)-chromaticity with luminance for observers VCS (top panel) and IY (bottom panel). Plot format is as for Fig. 2.

Fig. 4. Temporal forced-choice data for the combination of \( l \)-chromaticity with \( s \)-chromaticity for observers VCS (top panel) and IY (bottom panel). Plot format is as for Fig. 2.
for l-chromaticity. The data were fit by probability summation for all detection data and for edge-identification combinations of l-chromaticity with luminance and l-chromaticity with s-chromaticity. The powers of $k$ for these fits were 1.49 (detection) and 2.64 (edge identification) for combinations of l-chromaticity with luminance, 2.31 (detection) for s-chromaticity with luminance, and 2.36 (detection) and 1.57 (edge identification) for combinations of l-chromaticity with s-chromaticity. These values were similar to the fits for VS and IY. The equiluminant data showed better symmetry than that for VS and IY. The edge-identification data for s-chromaticity and luminance were not well fit by probability summation; they were fit by vector summation with an angle of 121 deg. This result indicates a lower level of opponency for observer LJ. The variation of this observer from the others may represent either the change from a foveal to an extramacular stimulus or intrinsic observer differences.

Discussion

The results for combining chromaticity with luminance were not what we expected. First, we expected a possible summation of the PC-pathway spectral signal with the PC-pathway achromatic signal, not an indication of stochastic independence of the underlying detection mechanisms. We interpret these data to mean that the population of cortical cells with primary PC-input combine luminance and chromaticity to varying degrees (Lennie et al., 1990; Landisman & Ts‘o, 2002a,b; Shapley & Hawken, 2002; Friedman, 2003). Our task taps some subsets of this population on the chromatic and achromatic axes. Presumably we tap other subsets when we combine chromatic and achromatic excitation.

Second, we expected independence of the KC-pathway spectral signal with luminance. Here however we found an opponent interaction: the $s$ signal subtracted from bright edges and summed with dark edges. Conversely, the $-s$ signal summed with bright edges and subtracted from dark edges. This result suggests a particular type of chromaticity-luminance interaction above the LGN. Although we could postulate particular types of cell that would behave like the data, we have no knowledge of such cells in the visual cortex. However, variability in reported cortical cells carrying chromaticity information is broad (Lennie et al., 1990; Conway, 2001).

Our data did agree with expectation for the equiluminant chromatic plane. The retinal spectral opponent chromatic plane $(l, s)$ differs from the perceptual opponent chromatic plane $(R−G, B−Y)$ as postulated by Hurvich and Jameson (Hurvich & Jameson, 1957, 1958; Jameson, 1972). Thus for the equiluminant data, the results were consistent with the interpretation that retinal excitation signals determined detection and edge identification.

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References


