Chromatic Changes in Relation to Binocular Summation Determined With Contrast Thresholds

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Abstract: We measured binocular summation for the detection of red–green chromatic, blue–yellow chromatic, and luminance contrast. The results indicated a higher degree of binocular summation for luminance contrast (reaching the level of neural summation) than for chromaticity contrast (probability summation), showing that the former is more effective than the latter for the binocular visual system, in agreement with studies on stereopsis and binocular summation for visual reaction time. © 2003 Wiley Periodicals, Inc. Col Res Appl, 28, 366–370, 2003; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/col.10179

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INTRODUCTION

Color in relation to binocular vision has been the subject of numerous studies in recent years. A notable debate has focused on the relationship between stereopsis and color, the issue here being the extent to which stereopsis is possible with the use of equiluminant (chromatic–contrast only) stimuli. The seminal study by Lu and Fender,1 which concluded that stereopsis is “color-blind,” prompted numerous studies,2–8 many of which contradicted the initial finding.2–6,8

Although many experimental studies have clarified the relationship between color and stereopsis at equiluminance, fewer studies have dealt with other binocular functions, such as binocular summation. The phenomenon of binocular summation offers numerous possibilities for studying spatial or temporal aspects of vision and thereby for elucidating the role of color in binocular compared to monocular vision.

Concerning spatial vision, Simmons and Kingdom9 studied binocular summation for compound stimuli (isoluminant red–green, isochromatic yellow–black, or some combination of the two), determining binocular and monocular contrast-detection thresholds. They found that binocular summation with chromatic stimuli, even when equiluminant, exceeded that expected from probability summation. Recently, Jiménez et al.10 found that reaction times for detecting the onset of a target showed greater binocular summation when the target was luminance-defined than when equiluminant.

In this work, we seek to contrast the results on binocular summation for visual reaction time10 with those reported by Simmons and Kingdom9 on contrast thresholds. Thus, we performed new experimental studies on binocular summation and color for spatial vision. We calculated monocular and binocular contrast thresholds for luminance gratings and along red–green and yellow–blue directions at equiluminance, using two spatial frequencies: 0.5 and 2.0 cpd (cycles per degree). Thus, we extended the Simmons and Kingdom9 study by testing yellow–blue stimuli and a new spatial frequency (Simmons and Kingdom used 0.5-cycle sinusoidal filters modulated by a Gaussian). Hence, the set of experimental conditions for comparing the binocular summation for luminance and chromaticity changes was greater. We have analyzed our results with the aim of determining the type of binocular summation—neural or probability—involved in contrast detection.

METHODS

Contrast thresholds were determined under both monocular (left and right; in these cases, one eye was covered with a
black patch) and binocular conditions. The stimuli were horizontally oriented, stationary gratings of spatial frequency 0.5 or 2.0 cpd. The gratings were vignette by a raised cosine envelope along the axis of modulation to avoid sharp borders. We selected low spatial frequencies to minimize the effects of chromatic aberrations. The overall phase of the stimulus was fixed at 0°. For luminance gratings, we used the standard Michelson contrast, defined as

$$C_i = \frac{L_{\text{max}} - L_{\text{min}}}{L_{\text{max}} + L_{\text{min}}},$$

(1)

where $L_{\text{max}}$ and $L_{\text{min}}$ are, respectively, the maximum and minimum luminance of the grating. The set of luminance stimuli consisted of 50 contrast values ranging from 1.0 to 0.001.

For the chromatic gratings, we defined the chromatic contrast $C_i$ as

$$C_i = \frac{E_{x_1} - E_{x_2}}{P_i},$$

(2)

where $E_{x_1}$ and $E_{x_2}$ are the chromatic channel outputs $i$ (red–green or yellow–blue), according to Boynton,11 for the colors at the peaks and troughs of the grating. Red–green responses are then calculated as $L - 2M$, and blue–yellow responses as $S - (L + M)$, where $L$, $M$, and $S$ are cone-excitation values for Smith and Pokorny12 spectral-sensitivity functions. $P_i$ is a normalization constant that limited the maximum contrast to unity when the monitor’s dynamic range was at a maximum. The CRT monitor can generate a limited chromatic gamut,13 so that only the color stimuli that can be produced. Thus, for a given chromatic axis, the gamut of available colors will be restricted within the crossing points of the axis and the lines that form the triangle of phosphors. This implies that for the red–green and blue–yellow chromatic channels, there will be a maximum excitation value for each axis, corresponding to the excitation difference of the crossing points with the phosphor triangle. However, because we have chosen the equienergy stimulus as the center of chromatic modulation for each axis, it is advisable for the excitation modulation to become symmetric with respect to the equienergy stimulus. This implies that, to calculate the maximum modulation available, we have to take twice the value of the difference between the minimum of the excitations for the two crossing points for each axis and the equienergy stimulus. Hence, $P_i$ is calculated as follows:

$$P_i = 2(E_{\text{eq}i} - E_{\text{eq}i})$$

(3)

where $E_{\text{eq}i}$ is the minimum excitation value for the two crossing points of axis $i$ and the phosphor triangle, and $E_{\text{eq}i}$ is the excitation value for the equienergy stimulus, both according to Boynton’s model.11 The value calculated for $P_i$ is much higher for the $b$–$y$ axis ($P_{b,y} = 28.06$ cd/m²) than for the $r$–$g$ axis ($P_{r,g} = 7.52$ cd/m²). The contrast reaches its minimum value of zero when both colors are the same and equal the chromaticity coordinates of the equienergy stimulus, which was chosen as the crossing point of the two chromatic axes. The set of available chromatic stimuli consisted of 50 contrast values for each spatial frequency, from 1.0 to 0.001.

To determine the isoluminance setting for each chromatic stimulus, we alternated the stimulus with the reference white at 20 Hz, and adjusted the stimulus luminance until minimum flicker was reported. The isoluminance value was calculated as the mean of three settings.14

The mean grating luminance was 21.50 cd/m² for luminance gratings but varied slightly for the chromatic gratings due to subject variability in the isoluminance settings. The stimuli were displayed on a SONY CPD17SF color monitor controlled by a VSG2/3 waveform generator (Cambridge Research Systems, Kent, UK) with 14-bit digital-to-analog converters. The calibration, made with a spectroradiometer Topcon SR-1, consisted of a set of 64 measurements of luminance for each of the phosphors. In our calibration procedure, we assumed that the phosphor outputs are independent of each other, as well as across the display, and that they are temporally stable.13

We determined contrast-detection thresholds using a temporal two-alternative forced-choice staircase procedure, in which the test stimulus appeared in one interval and a uniform equienergy stimulus in the other with 21.50 cd/m². By saying “one” or “two,” the subject indicated the interval in which the test stimulus appeared. The staircase procedure began with a high contrast value and was terminated after six reversals. The threshold was calculated as the mean contrast value over the last four reversals and corresponded to 67% correct detection. Each data point on the graphs showed the mean and standard error of six measurements. The viewing distance was 1.68 m (8.0° visual field). A chin rest fixed the head position. More details about the method can be found in García et al.14

Three experienced psychophysical observers, one male and two female, (JR, RG, and EV; 35, 28, and 30 years old, respectively) with normal color vision (Ishihara test and the Pickford–Nicolson anomaloscope) and stereopsis (stereo-fly tests) participated in the study.

RESULTS AND DISCUSSION

Figure 1 presents luminance contrast sensitivities for the three observers. In all figures, results have been normalized to the highest contrast sensitivity obtained to facilitate the comparison across conditions. The monocular data are the mean for both eyes (right and left). In 15 of the 18 conditions tested (2 spatial frequencies, 3 observers, luminance and chromatic contrast at equiluminance), contrast sensitivity did not differ significantly ($p > 0.05$ according to $t$-paired test) between the left and right eye.

The results show that for all observers, and at both spatial frequencies, contrast sensitivity is significantly greater under binocular compared to monocular viewing conditions. This confirms the results of previous studies.15,16 Contrast sensitivity was greater for the 2.0 cpd compared to 0.5 cpd...
luminance stimuli, in keeping with conventional contrast sensitivity data.\textsuperscript{15–17}

Figures 2 and 3 show the results for red–green and yellow–blue gratings at equiluminance. For all observers, binocular thresholds were significantly lower than the monocular thresholds for the two frequencies tested ($p < 0.05$, all cases). The graphs show the greater contrast sensitivity for the frequency of 0.5 cpd, a trend analogous to that shown in other works on this subject.\textsuperscript{17}

Binocular summation, defined as the ratio of binocular to monocular contrast sensitivity, is a unitless measure that allows the results from the luminance and chromatic stimuli to be directly compared. This definition allows us to quantify the performance of the binocular system with respect to the monocular system in the visual task studied.\textsuperscript{18} Figure 4 shows the mean binocular summation (average of the data corresponding to the two spatial frequencies used) for each observer for the luminance, red–green, and yellow–blue contrast conditions. Table I gives binocular summation values for all conditions and shows that binocular summation is greater for luminance than for chromatic contrast. Binocular summation for luminance contrast ranged from 39\% for RG to 48\% for EV, with a mean of 43.3\%, whereas for chromatic contrast, it ranged from 16\% for RG to 25\% for JR, with a mean of 21.25\%. There appears to be little effect of spatial frequency on binocular summation (average difference of 2.6\%), though with EV, the higher spatial frequency condition was greater by 5\% in the luminance case. No significant differences in binocular summation were found between the red–green and blue–yellow conditions.

It is useful to examine these results in terms of the two main types of binocular summation that have been proposed, namely, neural summation and probability summation.\textsuperscript{18} Probability summation indicates that the superior binocular performance is due only to a probabilistic origin: “two eyes see better than one,” because in each trial there are two chances of detecting the stimulus instead of one.\textsuperscript{9,18} Typically, a binocular summation value of 1.2 is indicative

FIG. 1. Normalized contrast sensitivity for luminance gratings; monocular versus binocular presentation. The monocular values are the average of the values for the right and left eye. Data correspond to two spatial frequencies: 0.5 and 2.0 cpd. Observers: EV, RG, and JR.

FIG. 2. Results for red–green gratings.

FIG. 3. Results for yellow–blue gratings.

FIG. 4. Mean binocular summation for the three conditions. The dashed line represents probability summation; the dotted line, neural summation. See text for details.

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of probability summation, although the exact value depends on the slope of the psychometric function for monocular detection. On the other hand, neural summation indicates some interocular excitatory interaction. Although there are many models of neural summation, the decision model of Campbell and Robson is generally used for contrast-threshold experiments. For this model, neural summation is approximately 1.41. For luminance contrast, we found the average binocular summation value to be 1.43, which is close to the 1.41 prediction. For chromatic contrast, on the other hand, our binocular summation values were close to probability summation levels, averaging 1.21. Our results support the idea that whereas for the detection of luminance contrast, there is an excitatory interaction between the eyes, for the detection of chromatic contrast, there is not.

Our results differ from those reported previously by Simmons and Kingdom, in that they found that binocular summation was at least as great for the detection of red–green chromatic contrast (and under some conditions, even greater) as for the detection of luminance contrast. This discrepancy may have arisen for various reasons. First, the spatial configuration of our stimuli were different. Second, we occluded one eye when measuring monocular detection, whereas Simmons and Kingdom used dichoptic presentation for both monocular and binocular conditions; the non-tested eye in the monocular condition was presented with a blank field of the same mean luminance and chromaticity as the tested eye in the binocular condition. Finally, our red–green stimuli would have had a slightly different chromaticity from those employed by Simmons and Kingdom, which were phosphor-based.

Our results are consistent with the previous study by Jiménez et al. using visual reaction time. They found that binocular summation for luminance contrast was 1.44 (similar to that in our experiments with spatial gratings), being 1.10 for chromatic contrast at equiluminance.

What might be the significance of our results for stereopsis? Some authors have reported that, for luminance contrast, a reduction in binocular summation is related to diminished stereopsis, although Simmons and Kingdom contended that some binocular summation can be detected in the absence of stereoscopic mechanisms, showing that the two mechanisms are not completely linked. For the observers who participated in the previous study by Jiménez et al., there was a correlation between binocular summation and stereopsis: Both the maximum disparity for stereoscopic identification ($D_{\text{max}}$) and binocular summation were lower for chromatic contrast than for luminance contrast. To determine whether the reduced binocular summation for chromatic stimuli found in our study was associated with relatively poor stereopsis, we measured $D_{\text{max}}$ with luminance, red–green, and blue–yellow random-dot stereograms (RDSs) for our three observers. $D_{\text{max}}$ was lower for the chromatic RDSs for all the observers. Our stereopsis results are consistent with the concept of two independent mechanisms for stereopsis, one luminance, and the other chromatic.

In summary, the results of both this and our previous study support the idea that binocular summation is worse for chromatic compared to luminance stimuli, and that binocular summation is correlated with stereoscopic performance. Future experiments are needed to clarify more precisely the relationship between binocular summation, chromaticity, and spatial vision.

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**TABLE I. Binocular summation for the different experimental conditions tested for the three observers.**

<table>
<thead>
<tr>
<th>Spatial frequency</th>
<th>Luminance</th>
<th>Red–green</th>
<th>Yellow–blue</th>
</tr>
</thead>
<tbody>
<tr>
<td>EV</td>
<td>0.5 cpd</td>
<td>2.0 cpd</td>
<td>0.5 cpd</td>
</tr>
<tr>
<td>RG</td>
<td>1.39</td>
<td>1.39</td>
<td>1.22</td>
</tr>
<tr>
<td>JR</td>
<td>1.44</td>
<td>1.45</td>
<td>1.25</td>
</tr>
<tr>
<td>Spatial frequency</td>
<td>Luminance</td>
<td>Red–green</td>
<td>Yellow–blue</td>
</tr>
<tr>
<td>EV</td>
<td>1.43</td>
<td>1.48</td>
<td>1.24</td>
</tr>
<tr>
<td>RG</td>
<td>1.39</td>
<td>1.39</td>
<td>1.22</td>
</tr>
<tr>
<td>JR</td>
<td>1.44</td>
<td>1.45</td>
<td>1.25</td>
</tr>
</tbody>
</table>

Note: Data correspond to the two spatial frequencies tested (0.5 and 2.0 cpd) and the way the spatial grating is generated: luminance and chromatic changes (red–green and yellow–blue) at equiluminance.

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