Stochastic independence of color-vision mechanisms confirmed by a subthreshold summation paradigm

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We have used a subthreshold summation protocol to analyze spatial color–color interaction.   By means of a CRT color monitor, we measured the threshold contours for a spatial frequency of 0.5 cycles/degree.   Heterochromatic flicker photometry was used to obtain isoluminance.   The results suggest that the blue–yellow (b–y) and red–green (r–g) contrast thresholds remained unchanged by the addition of fixed r–g and b–y subthreshold pedestals.   Our subthreshold summation data then support the stochastic independence of color-vision mechanisms derived from Mullen and Sankeralli's work [Vision Res. **39**, 733 (1999)] despite the differences that exist between the two experimental methods.   © 2000 Optical Society of America

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There has been extensive research on the interaction between luminance and color mechanisms and its influence on the properties of spatial visual processing.[1–4]   The most controversial results about the problem of the determination of possible interactions have been derived from subthreshold summation.[5–7]   This experimental paradigm is based on a probability summation model, according to which the independence of visual mechanisms is expected to lead to somewhat better detection if both channels are active.[8]

The results derived from subthreshold summation found by Gur and Akri[5] show evidence for linear summation.   These authors also offered an alternative form of presenting the data.   It consisted of comparing the observers' performance—percentage of correct responses—in detecting a pure color or luminance grating and their performance in detecting a combined grating.   Adding a subthreshold luminance (or color) contrast to the pure grating formed this combined grating.   In contrast, Mullen *et al.*[6] and Mullen and Sankeralli[7] have reported results compatible with an independence of visual mechanisms under the assumption of a probability summation model.   These results are derived from measurements of threshold detection of red–green (r–g) color contrast[6] and blue–yellow (b–y) color contrast[7] in the presence of a subthreshold luminance contrast.   One of the main differences between Mullen *et al.*[6] and Gur and Akri[5] is the experimental procedure employed to isolate the luminance and the chromatic channels.   While Gur and Akri[5] employed heterochromatic flicker photometry (HFP), Mullen *et al.*[6] used minimum motion.   In their more recent study, Mullen and Sankeralli[7] used nominal isoluminance and minimum motion for one of the observers to set the isoluminant ratios.   They argued that the discrepancies with Gur and Akri's results could be due to their use of HFP, as in this procedure the isoluminance is determined under very different spatial and temporal

conditions from those used in the threshold measurements.   In addition, Mullen and Sankeralli[7] have also used subthreshold summation to analyze color–color interaction.   They found results compatible with the assumption that both r–g and b–y color-vision mechanisms are independent at subthreshold levels.

In this work we attempt the analysis of color–color interaction by a subthreshold summation procedure, as Mullen and Sankeralli[7] did, but using an isoluminance HFP method similar to that employed by Gur and Akri[5] to isolate the visual mechanisms.   Mullen and Sankeralli argued that Gur and Akri's results were opposite from theirs because the HFP settings were not being obtained in the same spatial and temporal conditions as the threshold measurements.   If this is so, then we should expect to obtain results similar to those found by Gur and Akri, as our isoluminance ratios are determined with HFP.   The main difference between Gur and Akri's isoluminance determination method and ours is that we measured isoluminance for six different pairs of colors in each of the axes, instead of only one pair (one *r/g* ratio).   Following this determination, we will be able to clarify, in an indirect way, if the argument put forth by Mullen and Sankeralli is the true reason for the opposite results found by Mullen and colleagues and Gur and Akri.

Stimuli are horizontal stationary isoluminant chromatic gratings raised cosine, enveloped along the axis of modulation to avoid sharp border effects.   The overall phase of the stimulus is fixed at 0°.   We define the chromatic contrast C_i of the gratings as

$$C_i = (\mathrm{Ex}_1 - \mathrm{Ex}_2)/P_i, \qquad (1)$$

where Ex_1 and Ex_2 are the responses for the chromatic channel i (r–g or b–y), as developed by Boynton,[9] for the two colors between which the chromaticity is modulated to generate the grating; P_i is a constant value calculated to make the maximum contrast value of unity.   This

value is conditioned by the limits of our experimental device in the generation of color gratings. It is calculated as twice the minimum difference in channel excitation between the crossing points for each chromatic axis with the phosphor triangle and the equi-energy stimulus,

$$P_i = 2(E_{cpi} - E_{eqi}), \tag{2}$$

where E_{cpi} is the minimum excitation value for the crossing points of axis i and the phosphor triangle, and E_{eqi} is the excitation value for the equi-energy stimulus; both E_{cpi} and E_{eqi} values are calculated with Boynton's model. The value calculated for P_i is much higher for the b–y axis ($P_{b-y} = 28.06$ cd/m^2) than for the r–g axis ($P_{r-g} = 7.52$ cd/m^2).

The contrast reaches its minimum value of zero when the two colors are the same and equal the chromaticity coordinates of the equi-energy stimulus, which has been chosen as the crossing point of the two chromatic axes. We use eight different fixed pedestal levels of r–g and b–y contrasts, and we measure the corresponding b–y (or r–g) contrast detection thresholds following a procedure similar to that used by Mullen and Sankeralli.[7]

Isoluminance for each pair of colors is evaluated by a standard HFP procedure that uses the equi-energy stimulus with a luminance of 21.50 cd/m^2 as the reference white. Flicker frequency is fixed at 20 Hz, and the field size is the same as that used in the threshold measurements. Since the luminances derived from observers' matches were close to 21.50 cd/m^2 as the pair of colors was nearer the equi-energy stimulus, we measure isoluminance for six different pairs of colors in each of the axes, instead of only one pair. The mean grating luminance is 21.50 cd/m^2, varying slightly for some pairs of colors because of the isoluminance settings made by each observer. The stimuli are displayed on a Sony CPD17SF2 color monitor controlled by a VSG2/3 waveform generator (Cambridge Research Systems, Kent, UK) with 14-bit digital-to-analog converters. The calibration was made with a spectroradiometer Topcon SR-1 and consisted of a set of 64 measurements of luminance for each of the phosphors. The calibration procedure implied the assumption of the following hypothesis: spatial independence of the phosphors with a simple scale factor, temporal stability (within at least four months), and phosphor constancy.[10–12]

Detection thresholds are determined with a two-alternative forced-choice staircase procedure, in which the test stimulus appears in one of two time intervals and an uniform equi-energy stimulus with 21.50 cd/m^2 appears in the other interval. The subject indicated, by saying "one" or "two," in which interval the test stimulus appeared. The staircase procedure was finished after six reversals in the contrast were produced, and the threshold was calculated as the mean of the contrasts of the last four reversals and corresponded to a 67% level of correct responses. Each plotted threshold was obtained as the mean of at least three measurements. The viewing distance was 1.68 m (8.0° of visual field). A chin rest fixed the head position, and direct and monocular vision was used. The spatial frequency was fixed at 0.5 cycles/

degree (c/deg). Previous to the determination of the subthreshold summation curves, it was necessary to measure the detection threshold for the r–g and y–b axes to scale the measurements obtained in the summation procedure in threshold units. These measurements were made for a range of subthreshold combinations of r–g and y–b contrasts. For half of the threshold measurements for each curve, the r–g contrast was varied while the y–b contrast was fixed at a certain value (from 0.15 to 0.9 in threshold units). The amount of r–g color contrast necessary to reach the detection threshold was determined for each fixed y–b pedestal. For the remaining data points, the pedestal was a fixed amount of r–g contrast, and y–b contrast was varied until the observer reached the detection threshold. After the data points were obtained, the results were fitted with a probability summation model as described by Quick.[13] The fitted equation has the following form,

$$(r/g)^k + (b/y)^k = 1, \tag{3}$$

where r/g is the scaled r–g contrast, b/y is the scaled b–y contrast, and k represents the shape factor of the threshold function. If $k = 1$, then there is linear summation between color-vision mechanisms (a straight line joining the thresholds along the cardinal axes); $k = 2$ indicates an Euclidean-type summation (elliptical or circular fit); and greater values of k should be indicative of an amount of summation compatible with Quick's model for independent analyzers, taking into account that color channels can be assumed to be noisier than luminance detectors and have shown k values smaller than luminance pattern detectors in a previous study.[7] In the third case, if we represent r–g contrast threshold as a function of y–b contrast threshold, data should indicate no interaction between color-vision mechanisms.

Two male observers (JH and JL, 26 and 30 years old, respectively) with normal color vision were used.

Figure 1 shows results from subthreshold summation obtained for both cardinal axes and a spatial frequency of 0.5 c/deg. Linear interaction between color-vision mechanisms should be revealed in the figure by the presence of data points along the lines joining the cardinal thresholds (these lines correspond to $k = 1$). However, linear interaction does not occur for each observer, since data spread out from the linear prediction (dashed lines in Fig. 1). The points with b–y fixed pedestals are distributed parallel to the y axis. This means that the addition of different subthreshold amounts of b–y contrast does not alter the r–g threshold. When b–y pedestals are used, the corresponding error bars are presented in the figure along the horizontal axis (r–g axis). The same reasoning could be applied to the r–g fixed pedestals (with the associated error bars along the vertical axis). In the figure we also show best fits obtained by the least χ^2 method weighted by the inverse of the square standard deviations of the data points; minimum χ^2 calculated are 19.58 for JL and 43.06 for JH. The values of k are in both cases consistent with a model of independent processing by the postreceptoral color-vision mechanisms. Although the experimental paradigms were different,
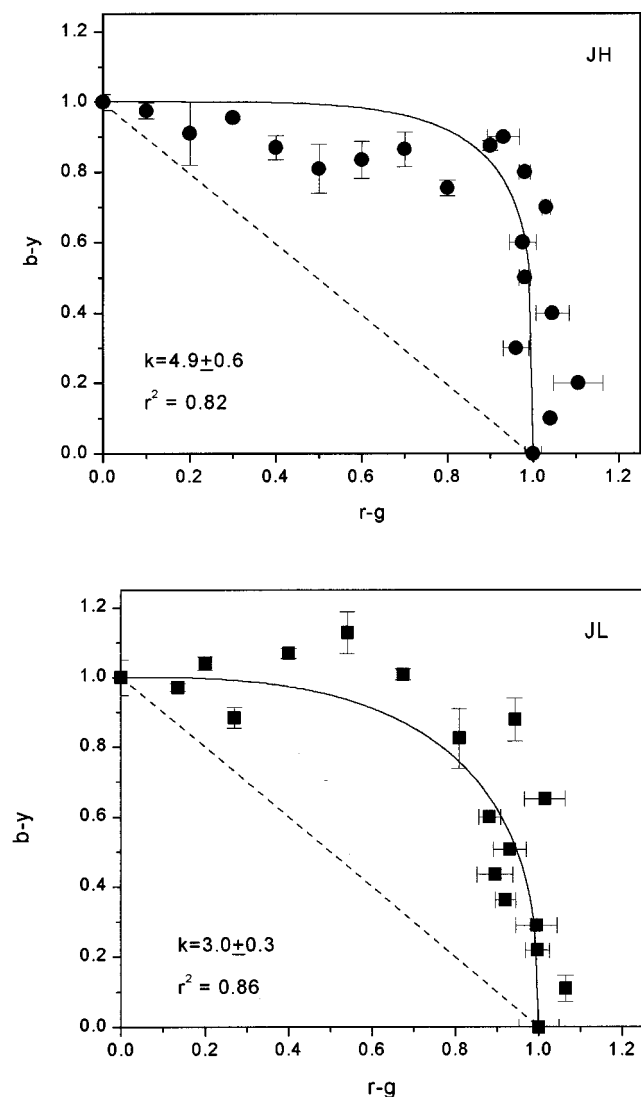
Fig. 1. Subthreshold-summation results (upper plot for observer JH, lower plot for observer JL) obtained as a function of pedestal contrast. Linear interaction between color-vision mechanisms is represented as dashed lines on the plots; best fits of the data by the least χ^2 method are shown as solid curves. Fitted k values [see Eq. (3)] and the correlation coefficient for the fit are also shown. Error bars represent ± 1 standard error.

minance, but by their determining only one isoluminance ratio at a fixed color contrast level. When using HFP, we noted that isoluminance ratios change as the contrast level of the stimuli decreases. So it is necessary to do several evaluations of the isoluminance ratio along each axis to ensure correct isolation of the chromatic channels. We then dissent with Mullen and Sankeralli's comments about the reason for their discrepancies with Gur and Akri's results.

Finally, within the assumptions of the probability summation model employed and the spatiotemporal conditions of the stimuli, our results are in agreement with the independence of color-vision mechanisms. This interpretation is not the only one compatible with Quick's pooling formula, as this formula can also be derived from the assumptions of a deterministic model with a nonlinear combination of detector's outputs, that are not allowed to vary independently (see Ref. 8, p. 169). This model would account for psychophysical variability by introducing noise at a later stage. It is still a matter for further studies to determine which model would be more appropriate to describe the behavior of visual spatial analyzers (still more so when we are talking of color spatial variations, which are much less studied than luminance patterns), but so far the results seem to favor Quick's model for independently variable multiple-analyzers.[14] Our results also leave open the question about possible interactions at suprathreshold levels, for which the observer's task would involve discrimination instead of detection.

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these results agree with the previous one derived from Mullen and Sankeralli[7]; the only difference is the average k value they obtained (averaged k of 2.27), which is somewhat lower than ours (averaged k of 3.95). Apart from the different spatial frequency we used, the discrepancies about the k values with Mullen and Sankeralli's results could be due to the relatively few data points in the corners of our contours, as Mullen and Sankeralli[7] suggest in their comparison of results for color–luminance contours with those previously obtained by Mullen et al.[6]

Since we have obtained results similar to those of Mullen and Sankeralli, with the only main difference being the HFP method used to set the isoluminance ratios, our results also lead to a rejection of the linear summation hypothesis according to Quick's model. In addition, we can conclude that Gur and Akri's results[5] were not conditioned by their choice of HFP for determining isolu-

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