Chromatic Contrast Detection in Spatial Chromatic Noise

Gianluca Monaci(1), Gloria Menegaz(2), Sabine Süsstrunk(3), Kenneth Knoblauch(4,5)

(1) Corresponding author.

Signal Processing Laboratory, Swiss Federal Institute of Technology,

CH -1015 Lausanne, Switzerland

E-mail: Gianluca.Monaci@epfl.ch

Telephone: +41 21 693 6874

(2) Department of Computer Science, University of Fribourg,

CH -1700 Fribourg, Switzerland

(3) Audiovisual Communication Laboratory, Swiss Federal Institute of Technology, CH -1015 Lausanne, Switzerland

(4) INSERM Unit 371, Cerveau et Vision

69675 Bron cedex, France

(5) Institut Féderatif des Neurosciences de Lyon, Lyon, France

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Abstract

The spectral properties of chromatic detection mechanisms were investigated using a noise-masking paradigm. Contrast detection thresholds were measured for a signal with a Gaussian spatial profile, modulated in the equiluminant plane in the presence of spatial, chromatic noise. The noise was distributed within a sector in the equiluminant plane, centered on the signal direction. Each stimulus consisted of two adjacent fields, one of which contained the signal, separated horizontally by a gap with the same average chromaticity as the uniform background. Observers were asked to judge on which side of the central fixation point the signal was displayed via a two-alternative, forced-choice (2AFC) paradigm. Contrast thresholds were measured for four color directions and three sector-widths at increasing levels of the average energy of the axial component of the noise. Results show that contrast thresholds are unaffected by the width of the noise sector, as previously found for temporally modulated stimuli (D'Zmura & Knoblauch, Vision Res 38: 3117-3128, 1998). The results are consistent with the existence of spectrally broadband linear detection mechanisms tuned to the signal color direction and support the hypothesis of the existence of higher-order color mechanisms with sensitivities tuned to intermediate directions in the color space.

Keywords: Chromatic discrimination, Noise, Spectral bandwidth, Masking

Introduction

Chromatic discrimination experiments have typically been interpreted in terms of two cone-antagonistic detection mechanisms (L-M and S-(L+M)) and a non-opponent, luminance-sensitive mechanism (L+M). The generality of this model has been questioned, however, by recent psychophysical studies showing evidence for chromatic mechanisms tuned to additional directions in color space (Krauskopf et al., 1986; Gegenfurtner & Kiper, 1992; D'Zmura & Knoblauch, 1998; Goda & Fuji, 2001). Nevertheless, agreement on this issue is still far from being reached (Giulianini & Eskew, 1998; Eskew et al., 2001).

Results from electrophysiological experiments in macaque monkeys support both hypotheses, depending on the level of visual processing. While the spectral sensitivities of neurons in the Parvo- and Konio-cellular layers of the lateral geniculate nucleus tend to be oriented along the two directions in color space suggested by discrimination experiments (Derrington et al., 1984), those of neurons in cortical areas V1, V2 and V3 are more uniformly distributed throughout color space (Lennie et al., 1990; Kiper et al., 1997).

A second question concerns the bandwidth over which discrimination mechanisms integrate spectral modulation in color space. Narrow bandwidths can only result from a mechanism in which photoreceptor signals are combined nonlinearly while a broader bandwidth results from linearity. Physiological studies indicate that thalamic and most neurons in V1 combine cone photoreceptor signals linearly (Derrington et al., 1984; Lennie et al., 1990). In contrast, cortical neurons in areas V1 and V2 with narrowly-tuned spectral sensitivities have been found (Lennie et al., 1990; Kiper et al., 1997).

Measuring the influence of noise modulated along one chromatic direction on the detection of a spatial pattern along a different direction, Gegenfurtner and Kiper (1992) reported the presence of mechanisms with a narrow spectral selectivity. These results were later challenged by D'Zmura and Knoblauch (1998), however, who demonstrated that thresholds for detecting a temporal Gaussian pulse modulated along a color axis were independent of the distribution of noise along an orthogonal axis, the result predicted if a linear mechanism mediates discrimination. In contrast, Goda and Fuji (2001) found that discrimination of noise textures from different distributions in the equiluminant plane was best modeled by narrow band mechanisms. A difference between these latter two studies is in whether chromatic differences were discriminated over time or space. Cardinal and Kiper (2003), however, studying the detection of chromatic Glass patterns obtained results similar to those of D'Zmura and Knoblauch.

The above results motivated us to reexamine the sectored-noise masking paradigm of D'Zmura and Knoblauch with the signal and the noise being distributed over space rather than time. We also introduce a nested statistical model for evaluating the linear mechanism hypothesis. The results obtained show that the mechanisms for color detection are insensitive to the variation of sector-width of the masking noise. The human visual system seems to mediate the detection of chromatic spatial patterns through linear, broadband detection mechanisms tuned to the direction of the signal in color space.

Methods

Subjects

The experiments were performed by two color-normal observers (ages 26 and 35 years) both well practiced in the psychophysical task, having participated in an extensive pilot procedure to choose appropriate experimental parameters.

Apparatus

Images were displayed on a Barco PCD 321 Plus 21" monitor driven by a standard video board with 8-bit digital-to-analog converter controlled by a Pentium III computer. Stimuli were created with MatLab 6.1 and displayed using WinVis for Windows. The characteristics of the phosphors were measured with a Minolta CS-1000 spectroradiometer and the monitor was linearized via gamma-corrected look-up tables. Observers performed the experiments at a distance of 50 cm from the screen.

Stimulus

The stimulus was a 10.5 by 5 deg rectangular field of mean luminance 44 cd/m^2 and CIE 1964 chromaticity coordinates (x,y) = (0.31, 0.32) with a black fixation point at the center. A 0.5 deg width vertical strip in the center separated two 5 by 5 deg fields of spatial noise. At the viewing distance, the resolution was approximately 2 min per pixel, and the noise elements subtended 18 min of visual angle (9 by 9 pixels). A spatially, isotropic Gaussian modulation (σ = 1.25 deg, truncated at $\pm 2\sigma$) along a chromatic axis was added to one side of the display, chosen randomly on each trial.

Chromatic properties of the stimuli were specified in the equiluminant plane of the DKL color space (Derrington et al., 1984). The principle axes in this plane are the L-M (0 deg) and the S (90 deg) axes with the origin through the background color. We arbitrarily set each axis to have unit response when stimulated by a mechanism-isolating stimulus with unit pooled cone contrast (Brainard, 1996). Signal modulation directions tested were along 0, 15, 75 and 90 deg. The 75 deg signal was chosen because pilot experiments showed it to be the direction for which detection was equally likely for mechanisms along the 0 and 90 deg axes under our stimulus conditions.

The noise was distributed in a sector of half-width θ of 0, 30 or 60 deg in the equiluminant plane, centered on the signal direction (D'Zmura & Knoblauch, 1998). The noise of each pixel was constructed by sampling independently from two uniform distributions centered on the background chromaticity. The first sample was drawn along the signal axis. The range of the uniform distribution, 2n, which determines maximum noise modulation along the axis, was an independent variable fixed within each session. The second noise sample was distributed along the chromatic direction orthogonal to the first one, and its range was determined by the value of the noise sample along the signal axis. The distribution of the two noise samples in the equiluminant plane can be described as:

$$\mathbf{N} = U_{[\pm n]}\mathbf{a} + \tan\theta U_{[\pm U_{[\pm n]}]}\mathbf{a}^{\perp} \qquad (1)$$

where **N** is the coordinates of the noise sample in the equiluminant plane expressed as a sum of vectors along axial, **a**, and orthogonal, $\mathbf{a}^{\perp}$, directions, $U_{[\pm m]}$ a uniformly distributed value between the limits plus and minus m (see Figure 1).

FIGURE 1 ABOUT HERE

Procedures

A 3down/1up 2AFC staircase method was used to estimate detection threshold for the signal modulation. Within a session, signal direction, axial noise modulation and sector width were fixed. On each trial, the sectored-noise was presented on both sides of the stimulus and the signal modulation appeared randomly either to the left or right of the fixation mark. Subjects were asked to judge on which side of the fixation point the Gaussian signal appeared. Each data point reported in the paper is the average of results from three staircases, each of length 48 trials.

Results

Figure 2 shows contrast threshold of the signal as a function of noise amplitude for the three sector-widths for each of the signal directions tested from one of the observers. For each condition, the dependence of threshold, s, on noise amplitude, n, is described well by the equation (Legge et al., 1987):

$$s^2 = e_o + kn^2 \qquad (2)$$

where the slope k and the intercept e_o are parameters estimated from the data.

FIGURE 2 HERE

For a given signal direction, if discrimination is mediated by a single, linear mechanism tuned to that direction, then the threshold vs noise curve that describes the data should be the same for each sector-width of the noise. The performances of such a linear mechanism should not be influenced by the variation of the width of the sectored noise. In contrast, the sensitivity to noise would be expected to decrease with an increase of sector-width if a single, intermediate non-linear (narrow-band) mechanism mediates detection. The sensitivity would be expected to increase if two off-axis linear mechanisms are responsible for detection (D'Zmura & Knoblauch, 1998). The data in figure 2 seem to be well described by the linear model, and do not show obvious deviations in the sense of the non-linear or off-axis mechanism models.

In order to assess the fit of the linear model, a statistical test was devised. In equation (2), we can assume the parameter e_o to be constant for each signal direction, as the zero-amplitude noise condition is common to each sector-width. The hypothesis then reduces to testing if the gain parameter, k, is constant as a function of sector-width. To evaluate this, we fit a nested pair of models to the data. In the first instance, equation (2) was fit to the data with the parameter e_o

held constant across sector-width and k allowed to vary, yielding a model with 4 parameters. This model corresponds to a general alternative which covers both the non-linear and the off-axis mechanism models. In the second case, equation (2) was fit to the data, with both e_o and k constrained to be fixed across sector-widths, yielding a model with just 2 parameters. The two models are hierarchically related or nested because the second model is a special case of the first. In order to compare the two models, the sums of square errors from the fits of the two models were compared. If the errors in the models are independent and normally distributed then the quantity:

$$F = \frac{\left(\hat{S}_0 - \hat{S}_1\right) \big/ \left(df_0 - df_1\right)}{\hat{S}_1 \big/ df_1} \qquad (3)$$

has the central distribution $F_C\left(df_0 - df_1, df_1\right)$, where df_0 and df_1 are the degrees of freedom for $\hat{S}_0$ and $\hat{S}_1$, respectively, the sum of squared residual errors under the two hypotheses (Dobson, 1990). The values of F calculated for both observers and all the signal directions are shown in Table 1. All values were smaller than the critical F-value indicating that the two-parameter model describes the data as well as a model with four. Threshold is independent of the sector-width. Thus, our data do not reject the hypothesis that discrimination is mediated by a linear mechanism tuned to the signal direction for all signal directions tested.

TABLE 1 HERE

Discussion

The results obtained show that a linear mechanism successfully describes the data resulting from our tests with sectored-noise masks for all chromatic directions tested and for both observers. The signal directions tested included two that were expected to isolate cardinal mechanisms, that is, the (L-M) and S-(L+M) mechanisms. In addition, two intermediate directions were tested. The highest noise amplitudes that we used were sufficient to raise signal thresholds by about a factor of ten in all cases. In addition, the largest sector-widths used distributed noise over an angle of 240 deg in our coordinates. The human visual system, thus, behaves as if discrimination of a spatial distribution of color is mediated by linear, broadband mechanisms tuned to the directions of the chromatic signal tested and over a wide range of masking conditions.

Our results agree with the findings of D'Zmura and Knoblauch (1998) in which the task was similar but the observers were required to discriminate a temporal chromatic variation and those of Cardinal and Kiper (2003) in which observers were required to detect chromatic Glass patterns. Earlier results from studies of visual search (D'Zmura, 1991) suggest as well that the human visual system possesses chromatic linear mechanisms tuned to intermediate directions.

Recently, Goda & Fuji (2001) reported that discrimination of spatio-chromatic distributions of noise were best modeled by narrowband (and, thus, nonlinear) channels, tuned to a variety of color directions. The differences between their results and ours could be due to the difference in the tasks. In their experiment, noise samples were drawn from within a region of the equiluminant plane described by a sinusoidal modulation of radial amplitude as a function of color direction. The observers' task was to judge whether two fields of noise of equal frequency and amplitude but differing in phase were drawn from the same distribution or not. There is a spatial component in the color distribution in our experiment that is not present in theirs. Thus our observers were searching for a Gaussian spatial modulation of color along a particular color axis in the noise, while they were asking observers to decide if the distribution of colors in the two noise fields were statistically similar independent of their spatial distributions. It is possible that such a task requires a more global integration of chromatic differences that requires the participation of higher level mechanisms.

In summary, our results support the hypothesis that the detection of chromatic spatial patterns is mediated through linear, broadband mechanisms in some instances tuned to directions of color space other than those found pre-cortically.

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Tables

Table 1

Values of $F = 3\left(\hat{S}_0 - \hat{S}_1\right)/\hat{S}_1$ and corresponding values of $\text{prob}(F \le F_C(2,6))$ for different observers and signal azimuths. The critical value for F is 5.141.

Observer	Signal Azimuth	F	$\text{prob}(F \le F_C(2,6))$
IO	0º	0.7393	0.5164
	15º	0.5207	0.6187
	75º	1.8381	0.2384
	90º	1.4596	0.3044
GM	0º	0.5719	0.5925
	15º	0.0625	0.9400
	75º	1.8895	0.2310
	90º	4.8101	0.0576

Figures and legends

Figure 1: Sectored noise of amplitude n that fills a sector in color space of half-width θ, oriented along the direction **a**.

Figure 2: Sectored noise masking of a signal of azimuth 0 deg (a), 15 deg (b), 75 deg (c) and 90 deg (d). Noise masking thresholds were measured for sector half-widths 0, 30 and 60 deg. Each data point represents the average of three staircases. Error bars represent the standard error of the mean. The dashed lines represent the best fitting curves to $s^2 = e_o + kn^2$. Results for observer IO.

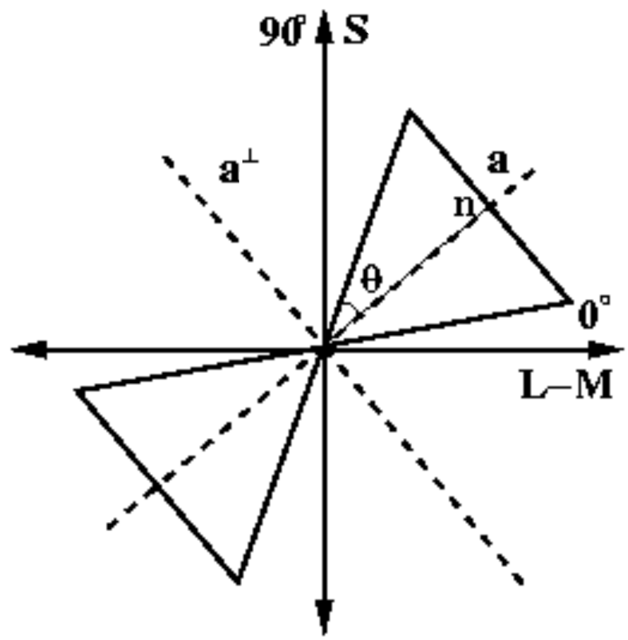

Figure 1

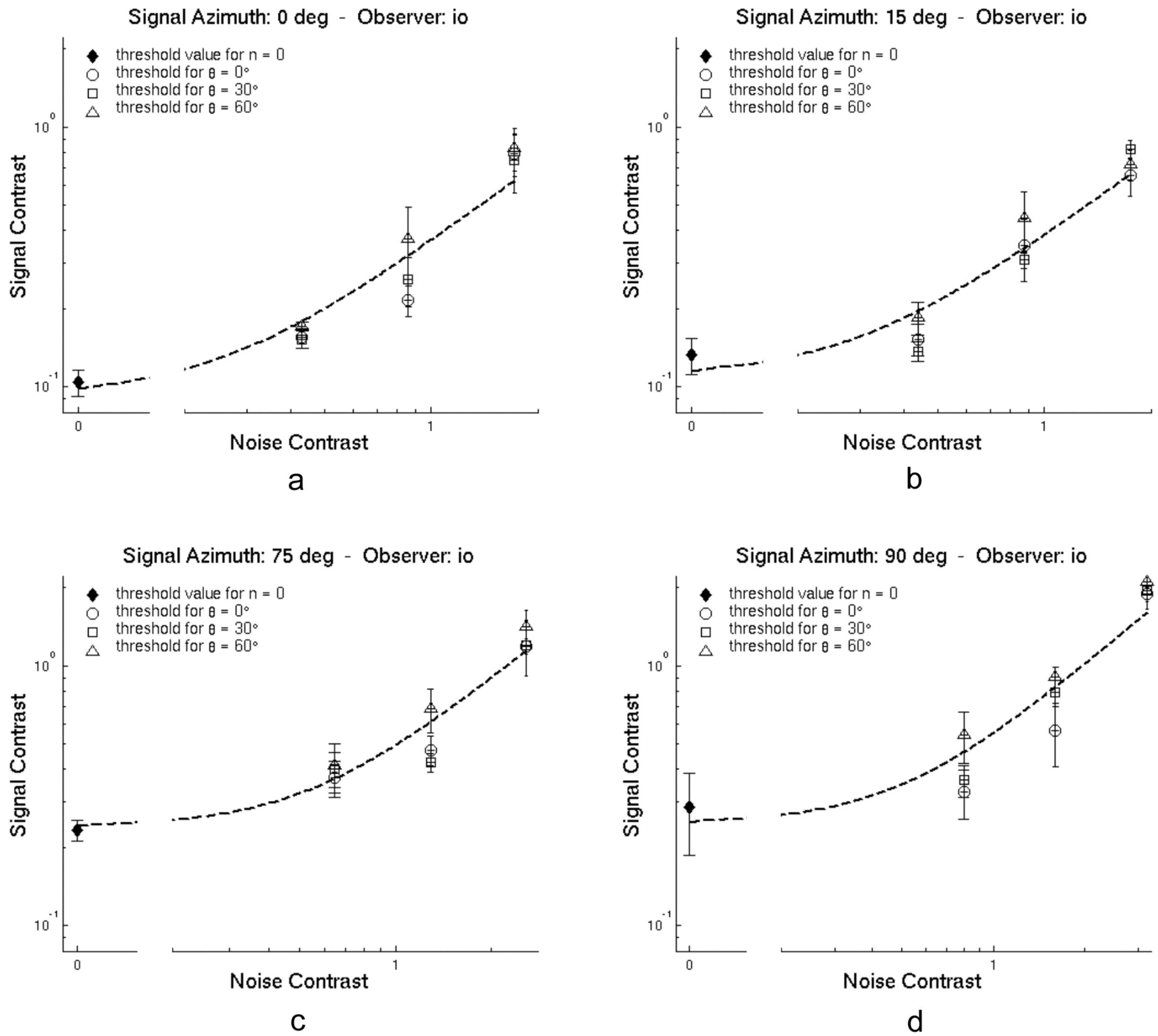
Signal Azimuth: 0 deg - Observer: io
Signal Azimuth: 15 deg - Observer: io
Signal Azimuth: 75 deg - Observer: io
Signal Azimuth: 90 deg - Observer: io
threshold value for n = 0
threshold for θ = 0°
threshold for θ = 30°
threshold for θ = 60°
Signal Contrast
Noise Contrast
a
b
c
d

Figure 2