

Contrast coding in the parvo-cellular system using simple reaction times

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ABSTRACT

We have proposed a model to analyse the role of contrast-coding process for the eye-brain-hand system at the large scale using simple reaction times (VRT). The model proceeds from the Information Theory adapted to the study of neural-coding dynamics. The theoretically derived equations accounts for Piéron's law and were evaluated by fitting mean VRTs obtained from a variety of chromaticity-scaled stimuli chosen along different red-green directions at isoluminance (L-M axis) in the CIE-1931 chromaticity diagram. The VRT model explained the contrast coding process at the threshold as well as the different activities account in the magno- and parvo-cellular pathways in relation to the contrast-sensitivity function.

1. INTRODUCTION

Previous works have proven that simple visual reaction time and contrast coding are mediated by the same sensory process, being possible to differentiate between the magno- and parvo-activity^{1,2}. A modified Piéron function have been proposed to establish a relationship between reaction time and contrast^{2,3}:

$$VRT = VRT_0 + (\beta / C) \quad (1)$$

in which VRT_0 is the irreducible, or asymptotic, term of reaction time, and C is the Michelson contrast or the RMS cone-contrast at isoluminance conditions^{2,3,4}. If VRT is plotted against $1/C$, the resulting slope, β , is assumed to be a contrast-gain sensitive index of the detecting mechanisms². However, little is known about the process immerse in β . The VRT model presented concerns with the foundations of Piéron's law in relation to stimulus intensity. Based on the entropy H-function, which describes the activity of photoreceptors and on the principle of information summation⁵, the theoretical derived equations support equation (1) and explain the contrast-coding process involved in the slope β . The model was tested to study the chromatic contrast responses in the parvo-cellular system using red-green stimuli at isoluminance conditions. The results obtained agree with the model predictions and extend those found in previous works for the achromatic system^{2,3}.

2. METHOD

A 1.5° circular spatial-uniform stepwise patches were presented in a calibrated CRT colour monitor connected to a microcomputer. The test stimuli were chosen along three red-green confusion lines⁶ (S-constant cone axis), RG1, RG2 and RG3. These lines originates at points ($x=1.0$, $y=0.0$) as shown in Figure 1. For each red-green line, a reference stimulus was selected to induce variations in terms of the RMS cone-contrast⁴:

$$\left[(L_C^2 + M_C^2 + S_C^2) / 3 \right]^{1/2} \quad (2)$$

where L_C , M_C and S_C are the Weber cone contrasts for the L, M and S cones against the corresponding reference stimulus selected. The equiluminance level established was 12 cd/m² and the heterochromatic flicker photometry method was used from an achromatic reference stimulus

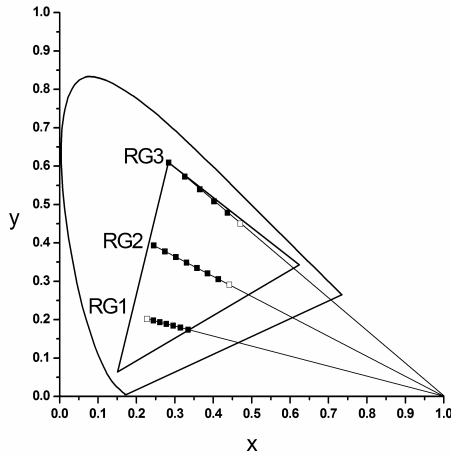


Figure 1: Stimuli chosen along each red-green confusion line in the CIE-1931 chromaticity diagram. Open squares indicate the reference stimulus used. Triangle shows the colour gamut displayed by the CRT colour monitor.

($x=0.332$, $y=0.333$, $Y=12$ cd/m^2), having the same field size as the test stimulus⁷. VRTs for manual responses were measure at isoluminance conditions using the standard procedure^{7,8}. The microcomputer was programmed to measure VRT with 1ms accuracy. Two normal colour observers (JA and MC) participated in the experiments. They were seated in a dark room and a chin rest was used to prevent head movements. The stimuli were observed with the right eye and with natural pupil. In each session, one red-green confusion line was chosen. The observers were adapted 3 minutes to the darkness, and additional 3 minutes to the corresponding reference stimulus. The test stimuli were presented randomly with a uniform foreperiod between 3 and 7 sec. Observers did not know which was the next stimuli in the sequence and therefore their task consisted only of responding as soon as possible pressing a button to an equiluminance variation in each L-M axis. In accordance with a “kill the twin” procedure⁹, those VRTs below 110 ms were discarded as false alarms while those exceeding 1500 ms were excluded as misses, similar to other studies of VRT^{1-3,7,8}. Observers performed a number

of sessions until reaching a distribution of no less than 80 VRT for each stimulus change under each experimental condition. The VRT value was taken as the arithmetic mean of the distribution. In addition, for each observer, the method of limits¹⁰ was used to obtain the differential chromaticity threshold corresponding to each reference stimulus. The field size as well as the adapting time were those established in the experiments⁷.

3. RESULTS

Norwich^{11,12} has presented a general theory of sensory receptors-sampling processes as a elementary form to derived a large number of physiological and psychophysical laws from an informational theoretical base, i.e., the entropy function H . In the case of the visual system, the *Entropic Theory of Perception* asserts that photoreceptors sample stimuli according with the H -function which governs the information received by the visual system from the environment (the drop in uncertainty, or, the equivalent, the gain in information). This sampling process is assumed to take place within a noise background so that the visual signal sampled is additively combined with noise. Starting from the differential entropy of a probability density function as a basic measure of information¹³, and considering an external stepwise visual stimulus with a fixed mean intensity I and finite duration t , the entropy function H of the photoreceptors can be written as:

$$H(I, t) = (1/2) \ln \left[1 + (\alpha I^n / t) \right] \quad (3)$$

where $H(I, t)$ represents the Entropy function (in natural units) whereas α and n are constants. Using Eq. (3), Norwich et al. developed a simple reaction time model that accounts the analytical form of Piéron's law^{5,12}. However, the experimental evaluation of the theoretical equations have only partially tested for luminance changes in dark adapting conditions⁵, without any considerations of the modified Piéron functions expressed in (1) in terms of the Michelson or the RMS cone contrast^{1,2}. Therefore, it is important to examine all these aspects. Starting from Eq. (3), simple reaction times are governed by *the informational principle of reaction times*. That is, the subject can react only when ΔH units of information (bits or natural units) are accumulated by the visual system⁵:

$$\Delta H = H(I, t_0) - H(I, t_{VRT}) \quad (4)$$

where t_0 is the value of t for which the H-function is maximum (it is assumed that the external visual stimulus is presented at $t=0$), and t_{VRT} the time to transmit ΔH natural units of information. Thus, it is possible to solve (4) for the visual reaction time $t_{VRT}^{5,12}$ to get:

$$t_{VRT} = \left(\left[\exp(-2\Delta H) / t_0 \right] - \left\{ [1 - \exp(-2\Delta H)] / (\alpha I^n) \right\} \right)^{-1} \quad (5)$$

When t_{VRT} and I , separately, tend to infinity, we obtain the differential intensity threshold respect to the reference intensity background (I_0), and the asymptotic or irreducible part of the VRT (VRT_0), respectively. Thus, for suprathreshold intensities ($I > I_0$), Eq. (5) can be expressed as:

$$t_{VRT} = VRT_0 + [VRT_0 (I_0 / I)^n], \forall I > I_0 \quad (6)$$

The resemblance to Eq. (1) can be achieved if we multiply by an arbitrary constant γ in the numerator and denominator of the second term in (6). The intensity ratio can be expressed in terms of the perceived or perceptual contrast Ψ by means of the Steven's law⁶, that is, $\Psi = \gamma I^n$, $(\gamma I_0^n / \gamma I^n) = (\Psi_0 / \Psi)$. For each colour direction j , since contrast matches exhibit the properties of homogeneity and transitivity, it is possible to assign a single scaling factor, ζ , in relation to the physical contrast¹⁴, i.e., $\Psi_j = \zeta_j C_j$ so, $(\Psi_0 / \Psi) = (C_0 / C)$. Thus, Eq. (1) follows if and only if:

$$VRT \equiv t_{VRT} = VRT_0 + (\beta / C), \forall \beta = VRT_0 C_0 \quad (7)$$

where C and C_0 represents the physical contrast (the Michelson contrast or the RMS cone contrast) and the contrast differential threshold, respectively. Therefore, in the case of the luminance system, the reciprocal of β can be considered as a measure of the luminance contrast-sensitivity function at different spatial frequencies². In the case of the red-green mechanisms, and according with the experimental configuration selected, the chromaticity thresholds measured by the method of limits should be scaled in terms of the value of C_0 derived from Piéron's law. As an example, Figure 1 shows the results found for the observer JA for the confusion line RG1, and their fit by Equation (1) in terms of the RMS cone-contrast. On the other hand, for each observer, table 1 shows the ratios in each red-green line at isoluminance.

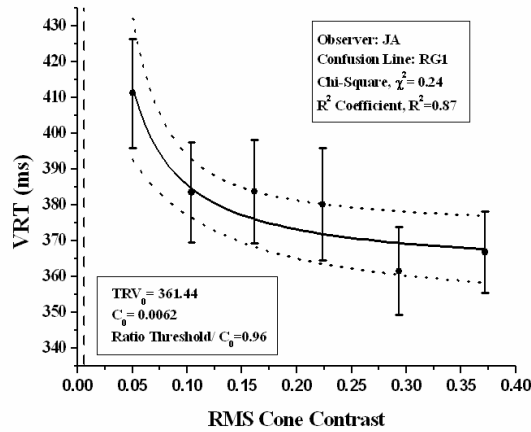


Figure 2: Observer, JA. Mean VRT values in the red-green chromatic channel at isoluminance. Error bars represent 95% confidence intervals. Confusion line RG1. Data were fitted to Eq. (1). Dotted lines represent the goodness of fit at a 95% confidence interval and dashed line indicates the chromatic contrast threshold value measured by the method of limits. The threshold ratio predicted as well as for the other red-green confusion lines are listed in Table 1.

Table 1: Ratio of the chromaticity threshold obtained by the method of limits to the contrast differential threshold obtained from Piéron functions (C_0)

Red-Green Line	Observer	Threshold/ C_0 Ratio
RG1	JA	0.96 \approx 1
	MC	2.78 \approx 3
RG2	JA	1.16 \approx 1
	MC	0.99 \approx 1
RG3	JA	1.05 \approx 1
	MC	1.90 \approx 2

4. CONCLUSIONS

We have reviewed the foundations of Piéron's law in colour vision in terms of stimulus intensity and Information Theory. The theoretically derived expressions support the results found previously for luminance signals² and suggest a relationship between Piéron's law and Steven's law in vision. Furthermore, the results found for the red-green signal extend those findings in the parvo-cellular system, concluding that the detection mechanisms responsible of contrast coding at the threshold (i.e., the contrast-sensitivity function) and simple reaction times, are mediated by the same neural process at isoluminance conditions.

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