A HUMAN BINOCULAR-VISION MODEL BASED ON INFORMATION THEORY FOR LUMINANCE AND CHROMATICITY AT ISOLUMINANCE SUPRATHRESHOLD CHANGES

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Abstract

We describe the temporal processing of the binocular-motor system at a large scale of integration. Simple visual reaction times (VRT) were measured manually for a variety of intensity-scaled stimuli for luminance and chromaticity at isoluminance changes. By comparing binocular and monocular VRT data within the context of information theory adapted to the study of neural coding, we propose a three-stage serially distributed binocular-vision model. For each type of signal, the model reveals a form of time-division multiplexing based on a monocular geometric mean as a combination rule, plus two-couple non-linear (companding) systems inserted into two communication channels that follow the Shannon-Hartley law.

Keywords: Visual-motor system; Colour perception; Temporal processing; Entropy function; Companding

1. Introduction

The binocular-vision system is a fundamental characteristic throughout mammalian species. In humans, this system provides a unifying single perception or cyclopean vision. Multiple visual phenomenon reveal the importance and complexity of this system, providing important neurobiologial and psychophysical data such as those found in the phenomenon of stereopsis, binocular summation or binocular rivalry [2,3, 12]. From these areas, a variety of growing disciplines seek to understand how the binocular system combines monocular inputs, notably through research on binocular cognitive models, the stereoscopic-correspondence problem, and their dynamics [3,8-9,14,21]. Although a variety of physiological studies have explained how simple and complex binocular cells make the monocular combination in the striate cortex, it remains unclear how binocular signals are taken into account in higher processing areas and in their internal and external dynamics with other non-visual areas such as the motor cortex. In the present work, we study these topics at the temporal-processing level. We manually measured simple visual reaction times (VRT) for both binocular and monocular vision, for different luminance and isoluminance stimuli under suprathreshold conditions. Since Helmholtz proposed reaction times as a supplement to other psychophysiological indicators, this non-invasive temporal parameter has provided key information on the neural conduction-time dynamics at the large scale of integration [13,15]. In a simple reaction-time procedure, this involved the simplest process (there is only one possible stimulus and one possible response). Thus, in visual perception, there is a noteworthy possibility to scale the magnitude of VRT with the intensity of the signal following Piéron's law [7,13,19]. On the other hand, since binocular VRT are shorter than monocular [3,10,21], binocular interactions are included

within this paradigm (a binocular-summation effect). Starting from these results, we have developed a new binocular model based on the existing information theory of neural coding adapted to the study of reaction times [16-17].

2. Method

The experimental stimuli were circular 1.5º patches of uniform colour on a dark background presented on a CRT colour monitor connected to a microcomputer. They were observed foveally by two normal observers with the natural pupil under three observational conditions: right and left monocular (in this case one eye was covered with a black patch) and binocular vision. The computer clock was programmed to measure VRT with 1 ms timing. To produce stimuli with specific CIE-1931 chromatic and luminance coordinates, we used a calibration method [11]. We used 12 achromatic stimuli with luminance values between 3 and 27 candela per square meter (cd/m^2) in increments of $2cd/m^2$. On the other hand, we generated chromatic variations at isoluminance along L&M and S cone axis (12 in each case), according to Boynton's two-stage colour-vision model [4]. This approach is more informative since it takes into account the first stages in vision processing presented in most colour-vision models. For each block of conditions (achromatic, red-green or yellow-blue signals), an achromatic stimulus of $15cd/m^2$ was chosen to produce suprathreshold variations. Stimuli were distributed symmetrically around this, and all could be clearly discriminated. This procedure scales the magnitude of VRT according to the polarity and intensity of the signals, enabling the adjustment of the mean value of VRT by Piéron functions (see [10] for more details).

3. A reaction-time model with memory based on information theory

Norwich et al. [17] presented a reaction-time model, derived from a receptor-sampling model without memory based on the information theory adapted to perception (commonly called The Entropic Theory of Perception), to predict the empirical Piéron equations [16,17]. Later, Norwich and Wong [18] generalized this receptor model considering the effects of sampling when a stimulus-intensity dependent local memory is activated. Despite that the equations proposed by Norwich et al. [17] are correct, they were written in a special form that obstruct an examination of the underlying neural-coding dynamics. At the same time, the case that takes into account local memory effects have not been developed, and therefore it would be informative to investigate these aspects. With respect to the particular case of visual perception, if the environment could be represented by a visual stimulus with a fixed mean signal intensity I, and duration of time t, the model proposed by Norwich and Wong [18] asserts that photoreceptors detect stimuli according to the following entropy function:

$$H(I,t) = \frac{1}{2} \cdot ln\left(1 + \frac{\beta \cdot I^{P}}{1 - e^{-at}} \right); \ \beta > 0, \ p > 0, \ a > 0, \tag{1}$$

where $H(I,t)$ represents the entropy function (the drop in uncertainty, or, the equivalent, the gain in information in natural units), where as β, p and a are constants, the latter representing the retinal-sampling frequency [18]. Expression (1) represents a generalization of the entropy function proposed by Norwich et al. [17], which can predict the empirical well-established Piéron functions. For this, introducing the existence of a threshold condition, the subject can react only when ΔH units of information are received [17]:

$$\Delta H = H(I,t_0) - H(I,t_{VRT}), \tag{2}$$

where t_0 is the value of t for which H is maximum (it is assumed that the stimulus is generated at $t=0$) and t_{VRT} signifies the time to transmit ΔH natural units of information. The informational principle of reaction time reflects the traditional assumption concerning the existence of serial processing stages in a VRT procedure [13], and thus it is involved in Piéron functions. Therefore, it is desirable to take it into account to express the functions calculated in a suitable manner. From (1), it is possible to solve (2) for reaction time (t_{VRT}). At the same time, if we take limits when t_{VRT} and I tends to infinity, we get the intensity threshold (I_0) and the asymptotic or irreducible part of the VRT (VRT_0), respectively:

$$\langle VRT \rangle = t_{VRT} \approx VRT_0 + \frac{1}{a} \cdot ln\left(1 + \left(\frac{I_0}{I}\right)^P\right), \forall \ (I \gg I_0), \tag{3}$$

where $<VRT>$ expresses the expected value associated with the reaction-time process. Equation (3) expresses a generalized version of the Piéron functions. Traditionally, the asymptotic term VRT_0 has been associated with the residual process contained in the VRT process, such as motor execution [7,13]. Nevertheless, this hypothesis is not admissible. If we consider the case when the intensity of the stimulus I, tends to infinity, transient temporal glare effects should appear, so that the visual system cannot operate as under normal conditions, and it is not possible to make a highly accurate motor response such as those involved in VRT experiments. Therefore, this term must include

another unknown process. If we express *VRT₀* as a sum of terms we get to the following expression:

$$VRT_0 = t_0 + \frac{1}{a} \cdot ln\left(1 + \left(\beta \cdot I_0^P\right)\right). \tag{4}$$

Now, Equations (3) and (4) enable us to describe the empirical Piéron functions for simple-reaction-time experiments as a three-serial-stage coding communication system with memory. If we accept the principle of efficiency of information representation [1,22], it follows that the term t_0 in (4) represents the coding time associated with the photoreceptor-signals encoder to reduce redundancy. At the same time, if we admit the generic diagram associated with a standard communications system [5, 22], the second term in (4) comes behind t_0 and represents the time associated with the transmission of the minimal quantity of information processed (a signal-to-noise ratio) within a continuous communication channel that follows the Shannon-Hartley law--that is, the second term represents the threshold characteristic processing time or t_{CPU}, which it is controlled by the retinal sampling time or *1/a*. Similar arguments establish the second term in (3) as the time associated with the transmission of a fixed quantity of information processed that comes from the second stage; that is, the second term represents the motor-processing time or t_{PM} (in our case, the act of pressing a button with the index finger).

4. A binocular-vision model

The visual-motor model presented implies a break with traditional models when the motor component is considered constant or with a positive correlation respect to the

stimulus intensity [20,13]. At the same time, our model takes into account the glare effects involved when the intensity of the stimulus becomes infinity (there is no motor processing) and thus in consonance with the experiment. On the other hand, according to the magnitude of VRT and Piéron's law, it establishes multiple distributed neural networks that depend on the type of signal (achromatic and chromatic at isoluminance) and its polarity (light, dark, red, green, yellow or blue). Therefore, to discern the combination rules in binocular vision, we fitted the VRT data to these functions, comparing the parameters obtained in each observational condition. For each type of signal-polarity induced, the result was described by a similar Piéron's law in both monocular and binocular vision. Comparing the coding time and the signal-to-noise ratios found at each stage ($\beta(I_0)^P$, $(I_0 /I)^P$), our results show the existence of a binocularly distributed neural network in both visual- and motor-processing levels:

$$t_{0B} = \frac{t_{0L}^{LR} \cdot t_{0R}^{LR}}{t_{0L}^{LR} + t_{0R}^{LR}} \text{, \textit{(binocular combination rule)},} \tag{5}$$

$$\left(\frac{S}{N}\right)_{B_{CPU}} = g_{CPU} \sqrt{\left(\frac{S}{N}\right)_{R_{CPU}} \left(\frac{S}{N}\right)_{L_{CPU}}} \text{, \textit{(visual-processing stage)},} \tag{6}$$

$$\left(\frac{S}{N}\right)_{B_{PM}} = \frac{g_{PM} \cdot g_{CPU}}{\sqrt[4]{\left(\frac{S}{N}\right)_{R_{CPU}} \left(\frac{S}{N}\right)_{L_{CPU}}}} \text{, \textit{(motor-processing stage)},} \tag{7}$$

where t_{0i}, represents the photoreceptor-coding time for the ith observational condition ($i \in B, R, L$; superscripts R and L denote the right and left monocular coding time when

both monocular channels are activated in binocular vision), $(S/N)_{ij}$ the signal-to-noise ratio for the ith observational condition at the jth stage and g_{CPU}, g_{PM}, the visual and motor gain factors. The visual-coding phase generates a multiplicative combination rule normalized to the sum of the monocular inputs (Expression (5)). This form of time-division multiplexing [5] is maintained in the successive stages, which, according to the communication-systems theory, could produce intermodulation distortion or crosstalk effects [5]. The signal will be demultiplexed, and attenuated (the roots in (6) and (7)) being processing (compressed $g_i<1$ or expanded $g_i>1$, depending on the type of signal-polarity induced), to become be multiplexed again in order to transmit to the next stage. This form of processing justified the decision centres subsequent to t_0 involved in t_{CPU} and t_{PM} and is compatible with the temporal asynchronies found in binocular-summation tasks [3,6]. On the other hand, our results show that these companding systems are coupled, in the sense that a compressed signal in the visual stage implies an expanded factor in the motor-processing stage and vice versa. Finally, the form of the signal-to-noise ratios found at the motor-processing level suggest a form of quasi-synchronous multiplexing system [5], when monocular inputs are accommodated in the motor memory to produce a motor-execution response with little variability.

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