Vision Research 125 (2016) 55–63

Contents lists available at ScienceDirect

Vision Research

journal homepage: www.elsevier.com/locate/visres

The time course of pattern discrimination in the human brain

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ARTICLE INFO

Article history:
Received 19 February 2015
Received in revised form 1 May 2016
Accepted 23 May 2016
Available online 14 June 2016

Keywords:
ERP
Instructions
Orientation discrimination
Gabor gratings
Decision difficulty

ABSTRACT

In electrophysiological experiments on visual pattern discrimination, decision difficulty was manipulated either via the physical characteristics of the test stimuli, or by changing the instruction given to the observer. Visual stimuli were rectangular matrices each composed of 100 Gabor patches having different orientations. Matrices differed in the number of Gabor patches with vertical, or horizontal, orientation. The observers' task was either to discriminate the dominant orientation or to detect collinear elements in the matrix. Relating task difficulty to performance, in the first experimental paradigm (detection of orientation) we obtained the conventional S-like psychometric function but in the second (detection of collinearity) the psychometric function showed a complicated U-curve. Matching between electrophysiological and psychophysical data and image statistical functions allowed us to establish the relative timing of the cortical processes underlying perception and decision making in relation to textural features. In the first 170 ms after stimulus onset coding of the low-level properties of the image takes place. In the time interval 170–400 ms, ERP amplitude correlated only with complex image properties, but not with task difficulty. The first effects arising from decision difficulty were observable at 400 ms after stimulus onset, and therefore this is probably the earliest electrophysiological signature of the decision making processes, in the given experimental paradigm.

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1. Introduction

Past literature reflects general agreement that a distinction exists between an initial perceptual processing of stimulus features, and a higher-level decision process that is responsible for behavioral reactions, but questions regarding their relative time courses remain debatable (see Nichols & Newsome, 1999; Schall & Thompson, 1999; VanRullen & Thorpe, 2001). With the help of event-related potentials (ERP) which have high temporal resolution it was shown the time window from approximately 100–200 ms at which identification of the visual stimulus occurs in the brain. This is true for faces (Jeffreys, 1996; Rousselet, Husk, Bennett, & Sekuler, 2008), for natural images of other objects (Thorpe, Fize, & Marlot, 1996; VanRullen & Thorpe, 2001) and also for textures (Fahrenfort, Scholte, & Lamme, 2008). However whether these differences between ERPs to objects and to non-objects reflect identification, and at what time the perceptual decision about the image occurs, is still unclear.

To address this question it is necessary to vary the difficulty of perceptual tasks during EEG recording, which will allow determination of ERP components which depend on the decision difficulty and, therefore, to establish the exact time at which the observer makes a conscious decision about properties of the object. For example, when the stimulus evidence was reduced by reducing the phase coherence of the image, an EEG component was identified approximately 220 ms after stimulus presentation which correlated with the visibility of the image and, therefore, with the psychometric curve (Philiastides, Ratcliff, & Sajda, 2006). This finding allowed the authors to relate that EEG component with the decision made by the participant. However in their experiments the decision difficulty was a function of only the image visibility and it may be that ERP deflection at 220 ms reflects the perceptual saliency as a part of task independent segregation-specific modulations in ERP (Rousselet, Pernet, Bennett, & Sekuler, 2008; Rousselet et al., 2010; Straube & Fahle, 2010; Straube, Grimsen, & Fahle, 2010).

Here we present a study in which decision difficulty was manipulated not only by the physical characteristics of the image, but also by changing the instruction given to the observer. Different instructions were used in experiments on the discrimination of

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http://dx.doi.org/10.1016/j.visres.2016.05.005
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texture, inspired by Field's study of textures consisting of Gabor gratings (Field, 1999; Field & Hayes, 2004; Field, Hayes, & Hess, 1993; Olshausen & Field, 2004). Such gratings are commonly used because they well match to the receptive field features to which cells in primary visual cortex are tuned (Watson, 2006; Watson & Ahumada, 2005; Watson, Barlow, & Robson, 1983). In the present study we developed a set of arrays in which the orientation of each Gabor patch was random, but the probability of vertical or horizontal patches (set among other orientations in the whole image) was different. Participants were given one of two tasks: one, to discriminate the predominant orientation within the matrix, and another, to detect collinear elements in the matrix. Therefore, two variables were manipulated in the experiment: higher-order statistics of the image (low-level properties of the image such as brightness and contrast remaining stable), and the instruction to the participant which changed the difficulty of the task. As a measure of decision difficulty we analyzed participants' reaction times and percentage of correct responses. The aim was to relate modulations in EEG activity to texture features (such as the degree of order in the matrix) and to the task difficulty and therefore, taking advantage of the high temporal resolution of ERPs, to establish the relative timing of cortical processes underlying perception and decision making. We hypothesized that relatively early ERP waves reflecting perceptual processes will depend exclusively on the images' properties, whereas later waves will reflect task difficulty, thus indicating the point at which the decision about the image occurs. Applying two different instructions to the same set of stimuli should arguably modulate top-down processes which we also hoped to evaluate in our study.

2. Methods

2.1. Participants

In total 51 volunteers participated in our experiments (median age 19 years, with a range of 18–35 years). All were right-handed, 49 of them were males. Of these, 25 participants received an instruction to discriminate the predominant orientation within the matrices, while another 26 participants had an instruction to detect collinear elements in the same set of matrices. All participants were free of current or past neurological or psychiatric disorders, had normal binocular vision estimated by The Worth Four Light Test, normal visual acuity without correction (higher than 1.0 by decimal notation), the range of astigmatism being no more than 0.25D estimated by auto refractometer Nidek Tonoref 2. Each subject was informed about the nature and the purpose of this study and gave written consent to participate. The study was conducted in accordance with The Code of Ethics of the World Medical Association (Declaration of Helsinki) and approved by the local ethics committee.

2.2. Stimuli and procedure

The participant sat comfortably in a dimly lit, sound-attenuated and electrically shielded cabin, in which no electrical devices requiring an AC power supply were operated. Stimulation was provided by a BENQ PB 8250 XGA projector which was placed outside the cabin. The refresh rate of the projector was 85 Hz. Rectangular matrices composed of 100 Gabor patches (a sine wave grating windowed by a Gaussian envelope) were used as stimuli, as in earlier studies (Fokin et al., 2008; Kharauzov, Shelepin, Pronin, Sel'chenkova, & Noskov, 2008). The matrices subtended a visual angle of 10 degrees at a viewing distance of 2.6 m; consequently, the size of each Gabor element was 1 degree. Gabor patches consisted of 4 black and white stripes, and their spatial frequency was 4 cycles per degree. Maximal Michelson contrast of gratings was 0.9. Orientation of Gabor patches varied from 0 to 165 degrees with step size 15 degrees. The matrices differed in terms of the number of Gabor elements with vertical and horizontal orientations. According to the number of co-oriented (either vertical or horizontal) gratings relative to other orientations, matrices could be either "random" with all possible orientations equally represented or "oriented" with the dominance of either vertical, or horizontal, orientations. The matrices were arranged into 8 groups according to their degree of orderliness: the number of Gabor patches sharing the same orientation was 8 (no dominant orientation, random matrix), 16, 24, 32, 40, 48, 56 and 64. Consequently, as orderliness increased the number of elements with other orientations proportionally diminished (Fig. 1). (Note that because the total number of gratings in the matrix was 100, we can also consider these numbers as percentages). Forty different matrices were generated for each level of orderliness, resulting in a total of 320 different visual stimuli. Special attention was paid to the minimizing of the probability of collinearly spaced Gabor patches (forming a figure like a snake) or any other contours and figures which could be formed by adjacent gratings. By visual inspection, matrices containing such pop out elements were discarded from the pool and changed by other realizations of matrices with corresponding percentages of collinear elements. Another criterion for discarding images was the presence of at least one pair of collinear Gabor gratings in matrices containing 8, 16, 24 and 32% of co-oriented elements. Matrices with more than 32% of co-oriented elements were selected for use only if they contained the shortest possible sequences of collinear elements. In other words, preference was given to matrices containing short, but widely distributed, collinear gratings, taking the image lines as a whole.

The main physical characteristics of matrices such as angular size, dimensions, brightness, contrast and spatial frequency were held constant, but images were differentiable in terms of their higher-level statistical properties. The first obvious determining factor was the number of elements sharing the same orientation, which linearly increased from the group of "random" matrices to the group of highly ordered (oriented) matrices (Fig. 2, left). The second factor, which derives from the first, is the relative dominance of one orientation over all other orientations. It was calculated as the ratio between the power of the horizontal (vertical) harmonic over the average power of resting orientations in the images' Fourier spectra (Fig. 2, middle). The third determining factor was the number of collinear Gabor patches in the matrix, i.e. adjacent elements which shared the same orientation.

Stimuli were composed in such a way that images with the degree of "orientational orderliness" less than 40% contained no collinear elements. As is clear from Fig. 2 (right), only a small number of collinear elements appeared in matrices with 40% of co-oriented Gabor patches. Starting from that point, the number of collinear elements in the matrices sharply increased with the degree of "orientational orderliness".

Matrices with predominantly vertical or horizontal orientations served as target stimuli and were presented for 1 s. in quasi-random order. Every target stimulus was replaced by the random matrix for another 1 s via an abrupt change of every Gabor grating's orientation. Afterwards, the random matrix was replaced by the next target stimulus. An advantage of this arrangement was that main physical parameters of the images (such as size, brightness and contrast) remained constant. Therefore, each trial lasted 2 s: 1 s presentation of the target stimulus and 1 s presentation of the masking random matrix which served also as a preceding image for a new trial.

In experiment 1 (Orientation task), participants were required to identify the predominant orientation in the target matrix, i.e. to make a choice between vertical or horizontal orientation, and

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