Chaos, Solitons and Fractals 93 (2016) 201–206

Contents lists available at ScienceDirect

Chaos, Solitons and Fractals

Nonlinear Science, and Nonequilibrium and Complex Phenomena

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

Theoretical background and experimental measurements of human brain noise intensity in perception of ambiguous images

Anastasiya E. Runnova[a,b], Alexander E. Hramov[a,b,*], Vadim V. Grubov[a], Alexey A. Koronovskii[b,a], Maria K. Kurovskaya[b,a], Alexander N. Pisarchik[a,c,d]

[a] Research and Education Center 'Nonlinear Dynamics of Complex Systems', Yuri Gagarin State Technical University of Saratov, Politehnicheskaya, 77, Saratov, 410054, Russia

[b] Saratov State University, Astrakhanskaya, 83, Saratov, 410012, Russia

[c] Center for Biomedical Technology, Technical University of Madrid, Campus Montegancedo, 28223 Pozuelo de Alarcon, Madrid, Spain

[d] Centro de Investigaciones en Optica, Loma del Bosque 115, Lomas del Campestre, 37150 Leon, Guanajuato, Mexico

ARTICLE INFO

Article history:
Received 5 June 2016
Revised 11 October 2016
Accepted 2 November 2016

Keywords:
Brain
Noise
Ambiguous image
Multistability

ABSTRACT

We propose a theoretical approach associated with an experimental technique to quantitatively characterize cognitive brain activity in the perception of ambiguous images. Based on the developed theoretical background and the obtained experimental data, we introduce the concept of effective noise intensity characterizing cognitive brain activity and propose the experimental technique for its measurement. The developed theory, using the methods of statistical physics, provides a solid experimentally approved basis for further understanding of brain functionality. The rather simple way to measure the proposed quantitative characteristic of the brain activity related to the interpretation of ambiguous images will hopefully become a powerful tool for physicists, physiologists and medics. Our theoretical and experimental findings are in excellent agreement with each other.

1. Introduction

The brain is one of the most sophisticated and enigmatic objects of comprehensive study attracting the burning interest of a broad scientific community [1–9]. Due to its immense importance and complexity, the brain research requires the combined efforts of scientists from diverse areas, including psychology, neurophysiology, medicine, physics, mathematics, and nonlinear dynamics. The multidisciplinary approach providing insight into the mysteries of the brain and a deeper understanding of mechanisms underlying its dynamics, opens promising opportunities for humanity with applications in medicine and neurotechnology in the nearest future.

The perception of ambiguous images [10,11] is just one very exciting task among an enormous number of open problems which appeared during recent intensive brain studies. Visual perception was often studied through perceptual alternations while observing ambiguous images [12–16], although perceptual alternations were also described for other modalities [17–19]. In addition, this phenomenon is tightly connected with the problem of categorical perception [20] (including non-human primates [21,22]). Even though the underlying mechanism of image recognition is not yet well understood, the metastable visual perception is known to involve a distributed network of occipital, parietal and frontal cortical areas [23,24]. The generally accepted concept that throws light on this phenomenon includes noise [25–28] inherent to neural brain cells activity originated from random neuron spikes [29].

Internal brain noise seems to play a crucial role in brain dynamics related to the perception activity [25–27] and other brain functions [30–33]. Different manifestations of stochastic processes in the brain, including the perception of ambiguous images, were extensively studied in terms of simple stochastic processes like the Wiener process [34–37] from the viewpoint of statistical properties [26–28,38,39]. The development of methods for quantitative measurement of the brain's stochastic properties can open up plenty of new opportunities for the study of the brain functionality and a diagnosis of brain pathologies. In the present work, we develop the quantitative theory and propose the experimental technique for measuring brain noise intensity related to the perception of ambiguous images. We carry out psychological experiments which confirm our theoretical findings and proposed methodological approach.

* Corresponding author.
E-mail address: hramovae@gmail.com (A.E. Hramov).

http://dx.doi.org/10.1016/j.chaos.2016.11.001
0960-0779/

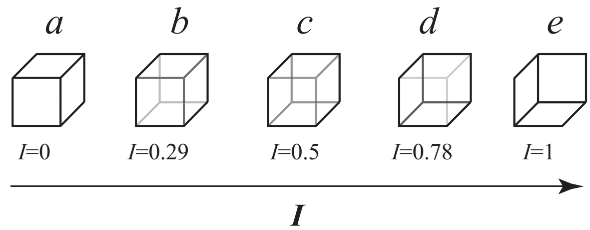

Fig. 1. Examples of distinct Necker cube images with different wireframe contrasts characterized by control parameter I.

2. Experimental study description

The experimental studies were performed in accordance with the ethical standards [40] and approved by the local research ethics committee of Saratov State Technical University. Twenty healthy subjects from a group of unpaid volunteers, male and female, between the ages of 20 and 45 with a normal or corrected-to-normal visual acuity participated in the experiments. All persons have provided informed consent before participating in the experiment. As an ambiguous image, we used the Necker cube [41]. The contrast of the three middle lines centered in the left middle corner, $I \in [0, 1]$, was used as a control parameter. The values $I = 1$ and $I = 0$ correspond, respectively, to 0 (black) and 255 (white) pixels' luminance of the middle lines, using the 8-bit grayscale palette for visual stimulus presentation. Therefore, we can define contrast parameter as $I = y/255$ where y is the brightness level of the middle lines in used 8-bit grayscale palette. The contrast of the three middle lines centered in the right middle corner was set to $(1 - I)$, and the contrast of the six visible outer cube edges was fixed to 1.

During the experiment $N = 16$ Necker cube images with different wireframe contrasts, i.e. with different values of the control parameter I (Fig. 1), were repeatedly presented to a person in a random sequence; each cube drawn by black lines was placed in the middle of a computer screen on a white background. All participants were well aware about the two possible orientations of the Necker cube, and both orientations were seen by all of them. All participants were instructed to press either the left or the right key on the control panel according to their first visual impression (left-oriented cube (Fig. 1(a) or right-oriented cube (Fig. 1(e)). Both the image presentation and the recording of personal responses were accomplished with the help of Electroencephalograph-recorder Encephalan-EEGR-19/26 (Medicom MTD). To demonstrate the grayscale stimulus we used a 24" BenQ LCD monitor with the spatial resolution 1920 × 1080 pixels and refresh rate of 60 Hz. The subject was located at a distance of 70–80 cm from the monitor with visual angle approximately equal to 0.25 rad. The overall observation time of each experiment was 32 min, each Necker cube with the fixed control parameter I_j ($j = 1, \ldots, N$) being shown randomly $K = 47$ times. In other words, during one experiment $M = N \times K = 752$ stimuli were presented to the observer. The schematic representation of the experiment paradigm is given in Fig. 2.

The choice of the durations of stimuli presentations, τ_i, as well as lengths of intervals between stimuli, s_i (see Fig. 2), plays the important role. Since the stimuli are presented to the observer intermittently, the effect of the stabilization of visual perception can take place [42]. The underlying mechanism of this stabilization effect is not clear yet (although there are known some model-based approaches, see, e.g. [43]), but obviously, that this effect consisting in persisting the visual perception between subsequent presentations of two ambiguous images can potentially affect the results.

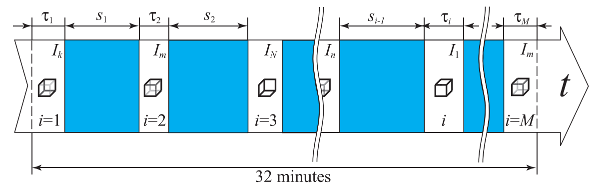

Fig. 2. The schematic representation of the experiment paradigm. The white rectangles correspond to the epochs with durations τ_i ($\tau_i \sim 0.5\div0.7$ s, $i = 1, 2, \ldots, M$). Within each epoch of the stimulus presentation the randomly selected Necker cube with one of the control parameter values I_j ($j = 1, \ldots, N$) is shown to the observer. Time intervals (with durations $s_i \sim 1.5\div2.0$ s when the different abstract pictures are demonstrated) between stimuli presentations are marked by dark rectangles. Two vertical dashed lines correspond to the start and finish of experiment, respectively. The total length of the experiment is 32 min when $M = 752$ times the Necker cube images are presented to the observer, with each of N Necker cubes (with the fixed control parameter value I_j) being shown exactly $K = 47$ times.

Therefore, the durations τ_i and s_i should be chosen in such a way to avoid the stabilization effect.

The mean duration of a visual percept is known to vary from one second to several minutes depending on each observer and stimulus conditions (e.g., [44]), whereas the mean response times are rather consistent and vary only by a few hundred milliseconds (see, e.g. [45]). The most common experimental length for each percept of the Necker cube was found to be approximately 1 s. [28]. Therefore, to fix the first impression of the person and avoid switches between two possible percepts the image exhibition was limited to $\tau \sim 0.5\div0.7$ s. This length of the stimuli presentation allows also reducing the stabilization effect [42] described above. Indeed, the probability of a configuration persisting until the subsequent presentation is known to be highly dependent on how long it was seen before the stimulus was removed [42]. Only when a perceptual configuration was seen consistently for the relatively long time before the stimulus disappearance, there is a high probability that it would persist to the next stimulus presentation. For the Necker cube this required time of the consistent observation is known to be about 1 s [42], and, therefore, taking the length of the stimulus exhibition τ below this value, we reduce the "memory" effect. The random sequence of the Necker cubes with the different values of the control parameter, I (see Fig. 2), also prevents the appearance of the perception stabilization. Lastly, to draw away the observer's attention and make the perception of the next Necker cube image independent of the previous one, the different abstract pictures were exhibited for about $s \sim 1.5\div2.0$ s between subsequent demonstrations of different Necker cube images.

For each value I_j of the control parameter I the probability $P_l(I_j)$ of the left-oriented cube (the left key choice) was calculated as

$$P_l(I_j) = \frac{l(I_j)}{l(I_j) + r(I_j)}, \quad (1)$$

where $l(I_j)$ and $r(I_j)$ are the numbers of clicks on the left and right keys, respectively, for the j-th Necker cube with the value I_j of the control parameter.

3. Theoretical approach

The probability of a subject to perceive the left-oriented image of the Necker cube $P_l(I)$ is, in fact, a psychometric function actively studied in psychophysics [46–48]. In the framework of classical approach, different empirical functions (such as Cumulative, Normal, Logistic, Weibull, Gumbel, etc.) are used to model experimentally obtained psychometric functions, with control parameters (first of all, threshold and slope) fitted with the help of different methods, e.g., maximum likelihood criterion or Bayesian criterion [47,49]. Although such an approach allows the quantitative description of the