ISSN 0096-3925, Moscow University Biological Sciences Bulletin, 2018, Vol. 73, No. 2, pp. 92–96. © Allerton Press, Inc., 2018.
Original Russian Text © R.K. Grigoryan, E.U. Krysanova, D.A. Kirjanov, A.Ya. Kaplan, 2018, published in Vestnik Moskovskogo Universiteta, Seriya 16: Biologiya, 2018, Vol. 73, No. 2, pp. 111–117.

PHYSIOLOGY

Visual Stimuli for P300-Based Brain-Computer Interfaces: Color, Shape, and Mobility

R. K. Grigoryan[a, *], E. U. Krysanova[a], D. A. Kirjanov[a], and A. Ya. Kaplan[a, b]

[a] *Chair of Human and Animal Physiology, Department of Biology, Moscow, 119234, Russia*
[b] *Lobachevsky Nizhny Novgorod State University, Nizhny Novgorod, 603950, Russia*
** e-mail: grraph.bio@gmail.com*

Received January 25, 2018; in final form, March 15, 2018

Abstract—The purpose of this study was to identify the impact of different discriminative features of stimuli in a P300 brain-computer interface paradigm on overall performance and evoked potentials. It has been shown that stimuli sets with a greater number of discriminative features yield better target selection accuracy. Target selection accuracy was significantly higher for the stimuli that differ from each other by color, shape, and semantics. Highest performance was achieved with the stimuli set containing the largest number of discriminative features, namely a set of nine different-colored letters. This result is mainly due to higher mean P300 peak amplitude for stimuli sets that contain more discriminative features. The results of the study can be used for designing a better user experience in brain-computer interfacing (BCI). Motion of the stimuli presentation point and characteristics of this motion (linear or pseudorandom) did not have any impact on BCI performance. This result is promising for future BCI designs with rapid serial visual presentation using mobile robots or augmented reality as stimuli presentation environment.

Keywords: brain-computer interfaces, electroencephalography, visual evoked potentials, psychophysiology, stroke, speech disorders.

DOI: 10.3103/S0096392518020037

INTRODUCTION

Brain-computer interface (BCI) technologies allow people to learn to generate signals for interaction with the environment through mental activity leading to specific changes in electroencephalogram (EEG) without using speech or movements [1]. One of the most reliable approaches to building BCI is a real-time detection of the specific EEG visual evoked potentials (VEP) in response to the activation of the stimuli that a participant focuses his attention on. This allows one to type a text letter by letter or to select different commands from those presented on a screen without making a muscular effort [1, 2]. This approach is based on the psychophysiological "odd-ball" paradigm, namely, that VEP emerging in response to the stimuli that draw attention of the operator (target stimuli) slightly differs in shape from the equivalent VEP emerging in response to indifferent or nontarget visual stimuli. A key difference of the VEP received in response to the target stimuli presentation is an increase in the positive P300 component, which appears with the latency of approximately 300 ms after the beginning of visual stimulus presentation [3].

Usually, visual stimuli (letters, pictograms, images, etc.) used for the operation of the P300-based brain-computer interface are displayed on a computer screen inside the cells of a square matrix [2, 4]. This creates a spatial value for the target stimuli that project onto the fovea located in the retina, whereas nontarget stimuli appear on the periphery of the visual field resulting in the differences in amplitudes of the corresponding VEPs. The majority of healthy individuals demonstrate high accuracy in P300-based BCI operation during short-term training [5]. However, during the extended operation of the BCI by both healthy individuals and, especially, patients with poststroke and posttraumatic disorders for whom this BCI technology is primarily designed for, it becomes difficult to achieve high accuracy of operation due to the need to continuously draw attention to one or another character of a matrix. Since the P300 component is the main indicator on which the VEP classification algorithms are based, mental fatigue results in a reduction of the P300 component and, therefore, the occurrence of errors in the classification of visual evoked potentials and command selection.

In recent years, due to the attempts of the practical application of the P300-based BCI, there is a need for the optimization and adaptation of stimuli environment in BCI for users to be able to run certain applications [6]. For long-term BCI operation in particular, it is necessary for users to minimize cognitive load with the retention of sustained attention to the stimuli.

This can be made by, for example, creating more attractive stimuli or by decreasing the visual load, etc. Mobile stimuli [7, 8], colored stimuli [9–11], stimuli of various shapes [12], and stimuli randomly moving on the screen [13] were used in different studies. However, none of those stimuli parameters were investigated under the same conditions; also, no observation was performed of the BCI operational efficiency of the stimuli of different modality and shape sequentially presented on the screen at the fixed spatial position, which not only facilitates perception but also expands the scope of practical application, such as the arrangement of a stimuli screen upon the controlled object (mobile robot or exoskeleton) [14].

The aim of the present study was to investigate the impact of different stimuli parameters (color, shape, and mobility) on the classification accuracy and the characteristics of visual evoked potentials occurring over the course of P300-based BCI operation with the stimuli sequentially presented at the fixed position of the screen which, in turn, may be static or mobile.

MATERIALS AND METHODS

Thirty-seven healthy volunteers aged 18–31 years were invited for the prospective study. Prior to embarking on the research, a written informed consent was obtained from all the participants in accordance with the form approved by the Biomedical Ethics Commission of the Biological Faculty of Moscow State University. The two following sets of stimuli presentation conditions were examined in the study: conditions related to the stimuli characteristics and conditions related to the mobility of the stimuli. Twenty people took part in the study of the conditions related to the characteristics of the stimuli (ten women and 11 men), and seventeen people participated in the study of the stimuli mobility (eight women and nine men). Monopolar 25-channel (O1, O2, Oz, PO7, PO3, POz, PO4, PO8, P3, P1, Pz, P2, P4, CP3, CPz, CP4, C3, Cz, C4, FC3, FCz, FC4, F3 Fz, and F4) EEG with linked earlobes reference was recorded using a NVX-52 amplifier (Medical computer systems, Zelenograd, Russia) with gel electrodes.

A participant sat in a chair in front of a monitor screen (24-inch monitor, 1920 × 1080, IPS-matrix) at a distance of 80 cm. During the experiment, the participant was instructed to refrain from movements, stay calm, try to avoid distraction and, when possible, not to blink his eyes.

Stimulus environment was presented on a computer monitor as a grey field where the stimuli from the different sets with an angular size of approximately 2.1 degrees were displayed. During the presentation, one stimulus was replaced by another occurring at the same position of the screen. The area of the stimulus presentation was either spatially fixed at the center of the screen during the whole experiment or moved in a straight line reflecting from the edge of a field at the rate of 5 degrees per second or moved in a random way changing the direction several times a second so that this motion pattern resembled pseudorandom motion.

In each session, the example of a symbol designating the target stimuli was located at the left of the screen. During the experiment, stimuli from a given set were randomly presented on the screen; among these stimuli, the participant had to calculate the number of appearances of the target stimuli and to ignore the rest (nontarget stimuli). The duration of the stimulus presentation was 50 ms and the pause interstimulus interval was 150 ms.

First, to build a classifier of the EEG reactions to the target and nontarget stimuli, each subject participated in a session consisting of ten cycles with different target stimuli. In each cycle, each stimulus of a given set, including a target one, was presented ten times. Therefore, 100 VEPs obtained in response to the target stimuli were included into a sampling used for the classifier learning.

After the successful classifier training (a variant of Fisher's linear discriminant algorithm), the participant was involved in test sessions the instructions for which were similar to those used for the learning sessions. At the end of each cycle of the test session, the participant received the following feedback: a symbol defined by the classifier as a target one was displayed on the screen. This symbol could be either correct, i.e., matching the target stimulus, or incorrect. The ratio of correctly selected by the classifier stimuli to their total number determined the accuracy of commands selection in the neurointerface. The maximum number of input cycles in a single mode was 12.

Two sets of conditions of the stimuli presentation were examined in the study. The first set contained five types of stimuli that differed in color and shape of the circles filling (Cyrillic letters or abstract symbols) and were displayed at the same position of a screen: nine different-colored circles, nine different-colored letters, nine letters of the same color (grey), nine different-colored abstract symbols, and nine abstract symbols of the same color (grey). Two types of stimuli positioned on the moving part of the screen were used for the examination of the sets of conditions related to the stimuli movement: nine different-colored circle and nine different-colored letters. The color set used for the circle and letter stimuli was same. Physical and perceptive stimuli intensities had not been tracked. The following three modes of presentation were created for each type of stimuli: stationary mode included presentation of the stimuli in a stationary point at the center of the screen, dynamic mode included linear motion of the point of stimuli presentation, and pseudorandom mode included motion of the point of stimuli presentation with pseudorandom change of direction.

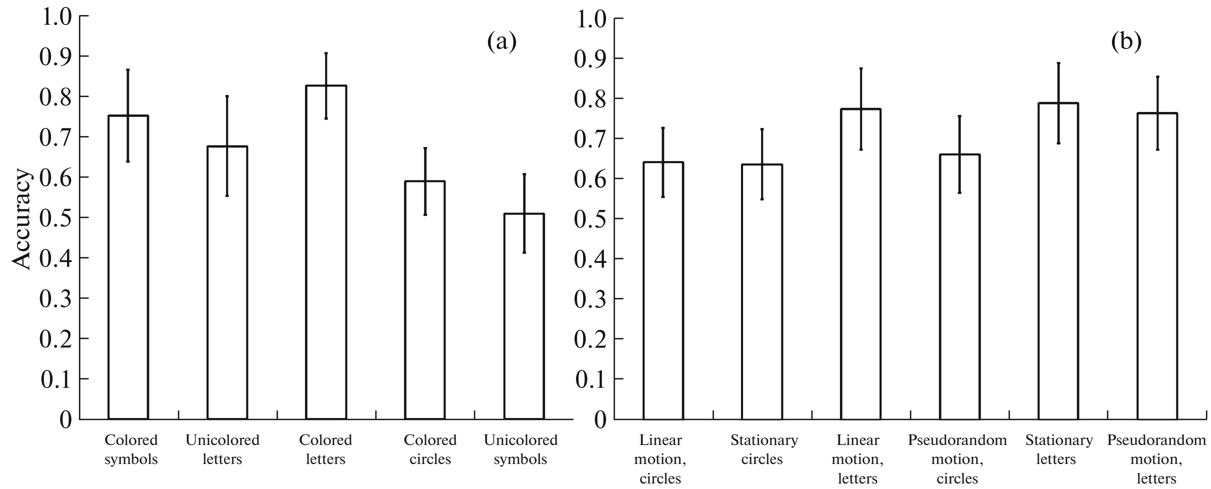

Fig. 1. Accuracy of selection of commands by the participants in all stimulation modes. (a) Study of the stimuli characteristics and (b) study of the pattern of the stimuli mobility. Data contain standard deviations.

The amplitude of the local maximum of the difference between averaged target visual evoked potentials and nontarget ones ranging from 250 to 500 ms after the beginning of stimulus presentation was considered as the amplitude of P300 wave.

Statistical data processing was performed with the Statsmodels 0.8.0 software [15] using the Type II sum of squares multivariate analysis of variance. The normality of distribution was assessed using the Lilliefors test and the White test was used for assessing the equality of dispersions.

RESULTS AND DISCUSSION

The assessment of the classification accuracy upon the stationary mode of stimulus presentation. The average accuracy of classification defined as the ratio of the number of correct neurointerface command selections to the total number of input attempts was 0.59 in the mode of colored stimuli of the same shape; it slightly exceeded the accuracy determined for the circles of the same color with abstract symbols (0.51) and was less then of unicolored letters recognition (0.68). At the same time, colored abstract symbols and letters were identified with greater accuracy: 0.75 and 0.82, respectively (Fig. 1a). Multivariate analysis of variance was used for the assessment of the statistical significance of these data. Statistical significance ($F = 6.9$, $p < 0.01$) was observed for the factor of the stimulus shape (three gradations) whereas no statistical significance was observed for the stimulus color (two gradations) which, however, might be associated with the heterogeneity of the color factor for filled and unfilled (circles without symbols) stimuli. Indeed, balanced design of the experiment consisting in comparison of all modes besides a mode with nine colored circles presented as stimuli has demonstrated statistical significance of the stimulus color ($F = 16.7$, $p < 0.001$); in other words, the accuracy of target stimuli selection is higher for the colored stimuli and for the stimuli of different shape (abstract symbols and letters). In this case, the maximum accuracy is achieved for the letters that, obviously, differ not only in their shape but also in content.

Therefore, color and specific shape of the stimuli significantly increase the confidence of P300-based neurointerfaces operation.

The assessment of the accuracy of stimuli classification when comparing the modes with moving and nonmoving stimuli. As can be seen in Fig. 1b, there is not much difference between the average accuracy of classification in a stationary mode (0.64) and the corresponding values in dynamic (0.63) and pseudorandom (0.65) modes. The same pattern is indicative for the circle-shape stimuli filled with the letters of different color; the values of the classification accuracy are as follows: 0.79, 0.77, and 0.77, respectively. As is the case with the stationary mode, the multivariate analysis of variance has demonstrated the significance of the stimulus type factor ($F = 15.6$, $p < 0.001$). The impact of the motion type was not significant.

Letters turned out to be much more effective for recognition in both the stationary and dynamic modes of the neurointerface. Lack of the negative effect of the stimuli mobility on the neurointerface operation accuracy is important for the development of neurointerfaces with stimuli positioned within the moving objects, such as moving modules of exoskeleton systems and simulators or mobile robots.

Analysis of the visual evoked potentials in a stationary mode of stimuli presentation. The maximum P300 peak amplitude and P300 latency, which is defined as the time from the onset of the stimulus presentation to the peak of the potential, were used when analyzing VEP (Fig. 2a). The same factors as ones used in the analysis

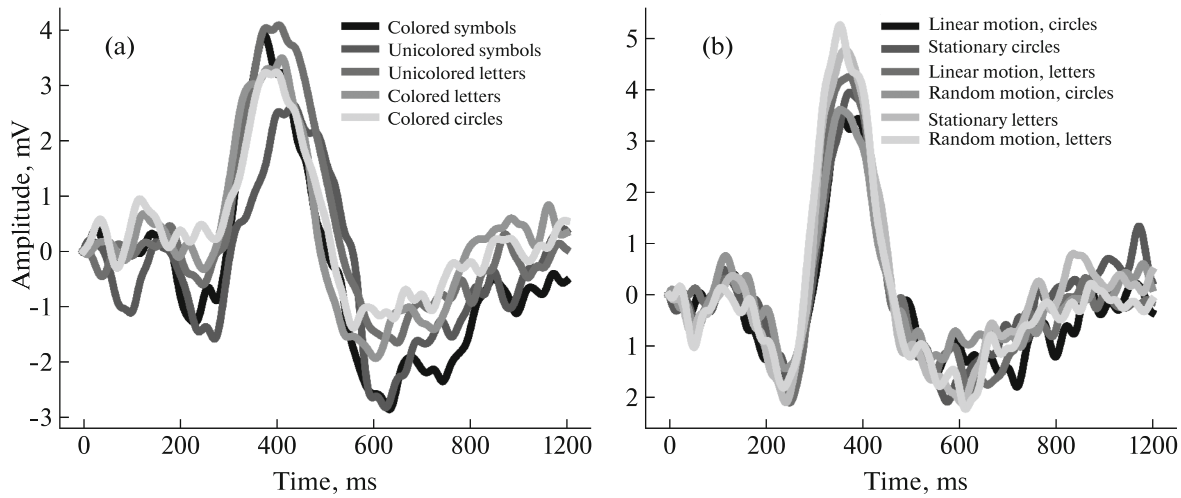

Fig. 2. Differential visual evoked potentials in the O1 site in the study of the (a) characteristics and (b) mobility of the stimuli.

of the classification accuracy were used when performing the multivariate analysis of variance. It has been observed that the type of stimulus significantly affects P300 amplitude recorded in the O1, PO3, PO7, and T6 sites, whereas the factor of stimulus color affects P300 amplitude recorded in the O1, O2, PO3, and PO4 sites and also affects stimulus latency in the PO4, PO7, PO8, and POz sites. The latency of the P300 peak is shorter for the colored stimuli, which indicates more rapid recognition of the colored stimuli. An increase in the amplitude of the VEP in response to the stimuli differing in a large number of discriminate features, likely, reflects coordinated work of the brain structures involved in the determination of the stimulus significance in different channels.

Analysis of the visual evoked potentials when comparing the modes with moving and nonmoving stimuli. The motion type factor does not affect the parameters of VEP. The type of stimulus affects both P300 amplitude (O1, O2, Oz, PO7, and PO8 sites) and latency (O1, PO4, and POz sites). Upward trend of increasing P300 latency in response to the moving stimuli is not significant. P300 peak amplitudes are larger for the letters, which is relevant to the data obtained during the stationary mode of stimuli presentation. P300 peak latency was shorter for the letters; moreover, the greater difference was observed for moving stimuli. Visual evoked potentials are presented in Fig. 2b. These data allow us to make a suggestion that the letter-shape stimuli are better perceived, which is reflected in a more complex task of visual tracking.

Examination of the relationship between the P300-based BCI operation efficiency when the stimuli are presented as symbols on a computer screen and the color, shape, and mobility of the stimuli has demonstrated that P300-based BCI works more accurately with the stimuli that, firstly, differ in color and, secondly, differ in shape. In addition, the accuracy of recognition in the P300-based BCI is higher for the stimuli whose content is familiar to the participant (letters). This is a theoretical mystery, because, if the participant calculates the cases of emergence of, for example, red-colored A letter among the nontarget different-colored letters, then it is easier for him to track only the color of a letter but not its details. Nevertheless, a homogenous red circle was detected in the neurointerface with less efficiency than a red letter or a pictogram presented in the same circle. The combination of the color and structure specificity within a target multimodal stimulus, presumably, activates the processes of cognitive perception to a greater extent than it does within a monomodal stimulus that, ultimately, leads to the changes in the VEP characteristics and more reliable response of the P300-based BCI.

Therefore, the data obtained over the course of designing the stimulus environment for the P300-based BCI allow us to recommend applying multimodal stimuli consisting of a combination of both specific color and structural components thus providing more comfortable and sustained work in the P300-based BCI by the users.

ACKNOWLEDGMENTS

This study was supported by the Innovation Support Foundation (project no. 11413).

REFERENCES

1. Powers, J.C., Bieliaieva, K., Wu, S., and Nam, C.S., The human factors and ergonomics of P300-based brain-computer interfaces, *Brain Sci.,* 2015, vol. 5, no. 3, pp. 318–356.
2. Farwell, L.A. and Donchin, E., Talking off the top of your head: Toward a mental prosthesis utilizing event-related brain potentials, *Electroencephalogr. Clin. Neurophysiol.,* 1988, vol. 70, no. 6, pp. 510–523.

3. Polich, J., Updating p300: An integrative theory of P3a and P3b, *Clin. Neurophysiol.,* 2007, vol. 118, no. 10, pp. 2128–2148.

4. Jin, J., Allison, B.Z., Kaufmann, T., Kubler, A., Zhang, Y., Wang, X., and Cichocki, A., The changing face of P300 BCIs: A comparison of stimulus changes in a P300 BCI involving faces, emotion, and movement, *PLoS One,* 2012, vol. 7, no. 11, e49688.

5. Guger, C., Daban, S., Sellers, E., Holzner, C., Krausz, G., Carabalona, R., Gramatica, F., and Edlinger, G., How many people are able to control a P300-based brain-computer interface (BCI)?, *Neurosci Lett.,* 2009, vol. 462, no. 1, pp. 94–98.

6. Kaplan, A.Ya., Neurophysiological foundations and practical realizations of the brain-machine interfaces the technology in neurological rehabilitation, *Hum. Physiol.,* 2016, vol. 42 N, pp. 103–110.

7. Jin, J., Allison, B.Z., Wang, X., and Neuper, C., A combined brain-computer interface based on P300 potentials and motion-onset visual evoked potentials, *J. Neurosci. Methods,* 2012, vol. 205, no. 2, pp. 265–276.

8. Guo, F., Hong, B., Gao, X., and Gao, S., A brain-computer interface using motion-onset visual evoked potential, *J. Neural Eng.,* 2008, vol. 5, no. 4, pp. 477–485.

9. Acqualagna, L., Treder, M.S., Schreuder, M., and Blankertz, B., A novel brain-computer interface based on the rapid serial visual presentation paradigm, *Engineering in Medicine and Biology Society (EMBC), 2010 Annual International Conference of the IEEE,* Buenos Aires, 2010, pp. 2686–2689.

10. Yeh, Y.Y., Lee, D.S., and Ko, Y.H., Color combination and exposure time on legibility and EEG response of icon presented on visual display terminal, *Displays,* 2013, vol. 34, no. 1, pp. 33–38.

11. Salvaris, M., Cinel, C., Citi, L., and Poli, R., Novel protocols for P300-based brain-computer interfaces, *IEEE Trans. Neural Syst. Rehabil. Eng.,* 2012, vol. 20, no. 1, pp. 8–17.

12. Proverbio, A.M., Burco, F., del Zotto, M., and Zani, A., Blue piglets? Electrophysiological evidence for the primacy of shape over color in object recognition, *Cognit. Brain Res.,* 2004, vol. 18, no. 3, pp. 288–300.

13. Ganin, I.P., Shishkin, S.L., and Kaplan, A.Y., A P300-based brain-computer interface with stimuli on moving objects: Four-session single-trial and triple-trial tests with a game-like task design, *PLoS One,* 2013, vol. 8, no. 10, e77755.

14. Tang, J., Zhou, Z., and Liu, Y., A 3D visual stimuli based P300 brain-computer interface: For a robotic arm control, *Proceedings of the 2017 International Conference on Artificial Intelligence, Automation and Control Technologies,* Wuhan, 2017, p. 18.

15. Seabold, S. and Perktold, J., Statsmodels: Econometric and statistical modeling with Python, *Proceedings of the 9th Python in Science Conference,* Austin, 2010, vol. 57, p. 61.

Translated by I. Matiulko