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*P*300-Based Brain-Computer Interface: The Effect of the Stimulus Position in a Stimulus Train

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Abstract—The most popular type of brain-computer interfaces (BCIs) are based on the detection of the *P*300 wave of the evoked potentials appearing in response to a stimulus chosen by the subject. In order to increase the speed of operation of these BCIs, it is possible to decrease the number of repeated stimulus presentations. It is associated with an increase in the relative importance of the response to the first stimulus in a train for correct recognition of the stimulus chosen. Event-related potentials (ERPs) in response to the first stimulus presentations are known to have their own specificity. Particularly, in many cases, the amplitude of the response to the first presentations is enhanced, which makes it very suitable for recognition in a BCI. However, this effect has not been studied to date. In this study, the ERPs recorded in healthy subjects in a standard BCI paradigm ($n = 14$) with ten presentations of stimuli or during triple-trial ($n = 6$) and single-trial ($n = 6$) presentations of stimuli in a modified BCI paradigm with moving objects have been analyzed. In both cases, first presentations of the target stimuli or single-trial presentation of the target stimulus were associated with higher amplitudes of ERPs. The opportunity to use specific differences between the responses to the first or single-trial presentations and the responses to later stimuli during their repeated presentations for improving high-speed operations in the *P*300-based BCI is discussed.

Keywords: brain-computer interface, event-related potential, *P*300 wave, *N*1 wave, first stimulus, single-trial.

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Brain-computer interface (BCI) is a modern neurotechnology that enables subjects to communicate with external electronic and electronic-mechanical devices on the basis of the recording of their electrical brain activity and without using muscles or peripheral nerves [1]. BCI-based technologies are applied in medicine for the rehabilitation of invalids in wheelchair and tetraplegia patients. In the near future, these technologies will occupy a niche in the area of operating of limb prostheses and orthoses, manipulators, and robotic devices; they will be also used for improvement of functional brain deficits in health-improvement medicine.

To date, several types of BCIs are known [2, 3]; however, the most widespread type is the so-called *P*300-based BCI, which was suggested in study [4] and operates with the cognitive component of brain event-related potentials (ERPs) [5]. In this BCI, various commands are coded by relevant external stimuli such as symbols presented on a display. The BCI recognizes a person's desired command by comparing the *P*300 wave amplitude [4] in response to short-term highlighting of each of these symbols. Recently, it has been shown that, in addition to a *P*300, the use of other ERP components, such as the occipital negative *N*1 component with a latency of 200 ms, is helpful [6–9]. Higher amplitudes of these ERP components in response to one of the stimuli indicate that this stimulus is the target stimulus preliminarily chosen by the subject. Not only control consoles but also sets of symbols for text printing may be used as stimulus matrices. In this case, BCI-based recognition of target stimuli allows a person to print a text without touching a keyboard [4, 10, 11].

In order to improve the accuracy of BCI-based recognition of a command chosen by a person, each of a set of stimuli is repeatedly presented. This procedure allows reducing the data's variability after averaging the responses to each specific type of stimuli. However, this protocol obviously decelerates BCI-based command recognition. BCI-based command recognition may be accelerated by more frequent presentation of repeated stimuli, but this effect is very limited. For example, in study [12], the optimal frequency of stimulus presentation was 4–8 per second, whereas an increase in the frequency of stimulus presentation up to 16 per second resulted in an impossibility of interface use in most subjects.

In order to increase the speed of BCI operations, algorithms for recognizing EEG responses to the target stimuli at a small number of their repeated presentations, including a single-trial protocol [13], should be improved. It is explicitly or implicitly assumed [13] that all responses to all stimuli are identical. However,

the response to the first stimulus is supposed to be more specific as compared to the responses to other stimuli, whereas its contribution to the final ERP is more prominent. In fact, the first target stimulus is not preceded by other target stimuli in the same stimulation train. In addition, standard protocols of BCI operation include a long interval of several seconds to tens of seconds between the trains of stimuli. Under these conditions, the amplitude of the *P*300 wave decreases after repeated presentations of target stimuli (see review [14]). The amplitudes of some other ERP components, particularly, the vertex potentials in response to tone, may decrease manifold after the second presentation of the target stimulus under specific conditions, such as short intervals between stimuli [15]. A decrease in the amplitude of the *P*300 during repeated presentation of stimuli depends on the type of response evoked by the stimulus [16]. In the standard method, the user of the *P*300-based BCI performs a task that is often used in psychophysiological studies and consists of mental counting of stimuli. However, the *P*300-based BCI has some specific features. First of all, the intervals between the stimuli are very short and constant. Most studies on the effect of the position of a stimulus in a train and the number of stimuli on the ERPs have been performed using substantially longer intervals; however, the duration of the interval between stimuli may influence the ERP amplitude in a complicated way (e.g., [17]). Furthermore, the occipital *N*1 component, which substantially contributes to the *P*300-based BCI operation in subjects who can control their eyes [7, 9], has been poorly studied (see [18] for review), and the effects of the position of the stimulus in the train on this component has not been investigated.

The dependence of the effect on the task conditions and specific features of the BCI indicate that additional experiments should be performed in order to answer the question of the presence of any substantial differences in the ERPs to multiple and single presentation of stimuli or the presentation of a small number of stimuli in the *P*300-based BCI. The results of these experiments will help to develop an optimal protocol of stimulus presentation in a BCI.

If the responses to single target stimuli and to the first stimuli among several target stimuli have their own specific features, then this will help to optimize algorithms of classification of brain responses and to improve the classification accuracy in the most rapid modes of *P*300-based BCI operations.

The purpose of the present study was to estimate the specificity of the responses to the first target stimuli in the framework of the *P*300-based BCI paradigm and to reveal any differences in the ERPs to the presentation of a single target stimulus or several target stimuli. In order to tackle this problem, we analyzed the data from the experiments performed earlier in a study on the effects of spatial factors on the ERP components in the *P*300-based BCI [19] and the experiments with single-trial and triple-trial stimulation protocols during a multisession performance in a modified *P*300-based BCI paradigm with the presentation of stimuli on moving objects [20]. This last paradigm is very important due to the expected progress of BCI-based technologies for controlling prosthetic devices, manipulators, and mobile robots [21].

EXPERIMENTAL

All experimental series involved healthy subjects who were acquainted with experimental conditions and signed their informed consent. The experimental procedure was approved by the Commission on Bioethics of Moscow State University. Statistical analysis was performed using the STATISTICA 7.0 software (StatSoft) with the help of Student's *t*-test for independent and dependent samples and analysis of variance (ANOVA); estimation of the effects of more than two factors with repeated measures was performed using multivariate analysis of variance (MANOVA).

Experiment 1. Recording with multiple stimulus presentations. 14 subjects, including six men and eight women (age 21–22 years) were involved in the study. A display for stimulus presentation was located at a distance of 80 cm from the subject's eyes. A table that consisted of 6×6 cells, containing letters and symbols of the Russian alphabet, was presented on the display screen. The angular sizes of the table and cells were $11.8° \times 11.8°$ and $0.7° \times 0.8°$, respectively. A stimulus represented the darkening of a letter due to the change of its color from gray to black [18, 22] for 125 ms. According to the standard protocol [4], the brightness of all symbols in the entire column or row changed simultaneously. There was an interval of 63 ms between the stimuli. The random darkening of 6 rows and 6 columns, i.e., 12 stimuli in total, constituted a stimulus train, which contained two target darkenings of the same letter in the column and row and ten nontarget darkenings.

Each subject had to focus their attention on the target letter and mentally count the number of darkenings that included this letter. Performance of the task with one letter represented one block, which consisted of five presentations of stimuli trains. The trains were not separated by additional intervals. Each subject had to do 20 target letters. Thus, a total of 200 target and 1000 nontarget stimuli were presented to each subject.

The EEG was recorded from seven electrodes: *Fz*, *Cz*, *Pz*, PO_7, PO_8, O_1, and O_2. The vertical electrooculogram was recorded using the electrodes located over and under the left eye. The EEG was digitized with a sampling rate of 512 Hz. Recording and control of the experimental procedure were performed using the BCI2000 system [23]. The epochs containing artifacts were excluded from averaging. On average, 4.3% of all epochs were excluded, and the number of excluded epochs was not more than 20% for each subject. The EEG was filtered in 0.5–20 Hz band using Butter-

worth's filter with compensation for a phase shift. In the averaged ERPs, we estimated the peak amplitudes of the *P*300 at the *Pz* electrode and occipital *N*1 in the PO_7, PO_8, O_1, and O_2 electrodes as the maximum and minimum values of a signal in the windows of [250500] and [120 270] ms, respectively.

Experiment 2. Recording with few stimulus presentations. In preliminary experiments, we tested the protocol with single-trial presentation and estimated the ERP stability in the modified *P*300-based BCI method, which was used in the main series. Five subjects, including one man and four women (age 21–22 years) were involved in the study. We earlier reported the absence of the effects of movement of the stimuli matrix on the ERPs in the *P*300-based BCI [24]; however, in order to revise the stability of the ERPs during the movement of stimulus positions relative to each other, we performed an additional study. Objects for stimulus presentation were circles with a diameter of 1.2°, which were indicated by figures from 1 to 3 or from 1 to 9, depending on the number of objects. These objects moved freely in the area with a size of 14° × 14° in the center of a display screen at a constant speed of 5°/s and changed their direction after contact with the other object or the border of the stimulus area, or were fixed in a table of 3 × 3 cells with a size of 4.3° × 4.3°, also located in the center of the screen. Unlike the previous series, the stimulus was the highlighting of the object that was not included in any columns or rows for 117 ms by changing the color of its margin and figure inside it from dark-gray to light-gray. Intervals of 83 ms were introduced between the stimuli. Stimulus programming was performed in a Matlab environment on the basis of a Psychtoolbox package. The EEG was recorded using an NVX52 amplifier and the CONAN-NVX software.

We did not observe any fundamental differences in the ERPs to the target stimuli presented according to the protocol with moving objects as compared to the ERPs presented according to the standard *P*300-based BCI method in this series in comparison with the data from the first series and the data in the literature. The ERPs in response to nontarget stimuli were practically absent in contrast to those that are usually observed in the *P*300-based BCI. However, we did not analyze these ERPs. Here, we analyzed records made in the modified *P*300-based BCI with moving stimulus positions.

In the main series with moving stimulus positions, twelve subjects, including three men and nine women, were involved in four sessions performed on different days with a minimum interval of two days between them. All subjects were randomly divided into two groups: group '1' was always involved in single-trial experiments and group '3' was always involved in triple-trial experiments.

We developed a game modification of the *P*300-based BCI [20, 25] and used it in this study. During every session, after adjustment or learning of a classifier on the basis of Fisher's linear discriminant [26] according to the protocol with eight stimuli trains with a duration of approximately 4 min, the main part of the session started. During this part, the subjects were to construct a picture from separate elements. Each picture consisted of nine elements, from which circles 2.15° in diameter were cut. These circles or balls moved at a speed of 5.4°/s in the game area 14° ×14° in size and changed direction after contact. The stimulus was the highlighting of a ball for 125 ms, i.e., an increase in the picture's brightness. Each stimulus train consisted of random highlighting of one target and eight nontarget balls without any intervals between highlightings. Moreover, each ball was not highlighted two times in a row. The target ball was indicated to the right from the main area. For convenient detecting of the target ball and tracking it, each ball was marked with a letter of the Russian alphabet. Work with one target ball represented one block, consisting of one (group '1') or three (group '3') stimulus trains.

Immediately after the subject found the target ball in the area, they pushed a mouse button; 3 s later, stimulation started. The subjects had to carefully track the target ball and mentally point each highlighting of the target ball (group '1') or mentally count each of three highlightings of the target ball (group '3'). If a classifier correctly recognized the target ball, then this element was added to the general picture with the ball kept in the field and the other target ball was presented. Otherwise, the subject was considered to have made an error, and the same ball remained a target. The subject had to construct a picture, collecting the elements from left to right and from top to bottom. One game consisted of constructing one picture, and it continued until all nine elements were consecutively placed into the picture or ten errors were made. Each subject in each session played ten games, and the pictures were different for each subject in all sessions.

The EEG was recorded and digitized with a sampling rate of 500 Hz from six electrodes: *Cz*, *Pz*, PO_7, PO_8, O_1, and O_2. The reference electrode was located on the right earlobe. Simultaneously, we recorded potential on the left earlobe and recalculated the EEG relative to the common electrode on the ear lobes. The unipolar EOG was recorded using the electrodes located over the left eye. The epochs containing artifacts were excluded from averaging in 1.6% of all subjects in all sessions for group '1' and in 2.0% in group '3'. The EEG was filtered as described for Experiment 1. The peak amplitudes of the *P*300 component in the *Pz* electrode and the *N*1 component averaged in the PO_7, PO_8, O_1, and O_2 electrodes were determined as described for Experiment 1 in windows of [250 500] and [120 250] ms, respectively.

RESULTS

Experiment 1. Recording with multiple stimulus presentations. In Fig. 1, the values of the *N*1 and the *P*300

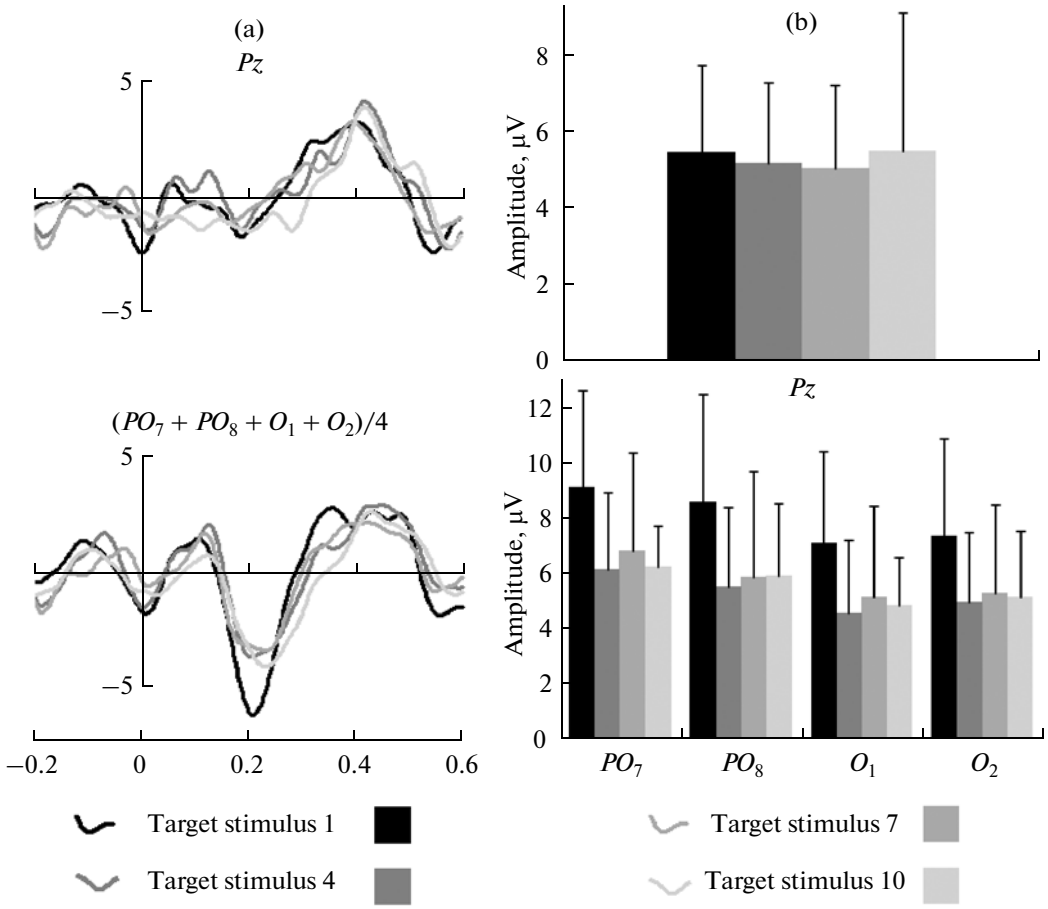

Fig. 1. *N*1 and *P*300 components in responses to the 1st, 4th, 7th, and 10th target stimuli. (a) Group-averaged ERPs at the *Pz* electrode demonstrating a *P*300 wave (upper curves) and in the occipital PO_7, PO_8, O_1, O_2 electrodes demonstrating an *N*1 component (bottom curves). For each subject, 20 responses to each type of stimuli were averaged. Start of stimulus presentation corresponds to 0 s on the time axis. Abscissa: time, s; ordinate: amplitude, μV. (b) Amplitudes of the *P*300 component at the *Pz* electrodes (upper panel) and the *N*1 component at the PO_7, PO_8, O_1, O_2 electrodes (bottom panel). Data are presented as mean and standard deviation ($n = 14$).

amplitude in response to the first target stimuli and also the fourth, seventh, and tenth target stimuli are shown. For *N*1, we performed two-way ANOVA with repeated measures, where the position of the stimulus and location of the electrode were used as factors. The effects of both factors were significant ($\lambda(3, 11) = 0.37$, $p = 0.011$ and $\lambda(3, 11) = 0.09$, $p < 0.00001$), whereas interaction between the electrode and the stimulus position was not observed ($\lambda(9, 5) = 0.29$, $p = 0.40$). The difference between the amplitudes of responses to the first and the other positions, which were analyzed in the occipital electrodes was 2.5–3 μV. According to one-way ANOVA, the *P*300 amplitude did not depend on the position of the target stimuli ($\lambda(3, 11) = 0.95$, $p = 0.9$).

Similar results were observed after comparison of the *N*1 and the *P*300 amplitudes in the responses to the first target stimuli and in the averaged response to all target stimuli. Differences in the amplitudes at the PO_7, O_1, O_2, and PO_8 electrodes were 3.0, 2.5, 2.6, and 2.6 μV, respectively, and the maximum amplitude was revealed at the PO_7 electrode, where the *N*1 amplitude only in response to the first target stimulus was 9.1 μV, whereas, after standard averaging of all target epochs, it was 6.1 μV. The effects of the factors "first stimulus versus averaging of all stimuli" and "the location of the electrode" on the *N*1 amplitude were significant ($F(1, 13) = 33.9$, $p = 0.00006$ and $\lambda(3, 11) = 0.12$, $p = 0.00002$, respectively), whereas the interaction between the factors was nonsignificant ($\lambda(3, 11) = 0.61$, $p = 0.13$). After averaging of the responses to the first target stimuli, the *P*300 amplitude at the *Pz* electrode was 1.3 μV higher compared to the averaged amplitude of the responses to all target stimuli, but this difference was nonsignificant ($t(13) = 1.99$, $p = 0.07$).

Experiment 2. Recording with few stimulus presentations. In Fig. 2, the ERPs evoked by single-trial or triple-trial presentations of the stimuli and the amplitudes of the *N*1 and the *P*300 components are shown. Data on the *P*300 amplitude of one subject in each group were excluded from analysis because, instead of *P*300, in these subjects, a positive wave with a latency

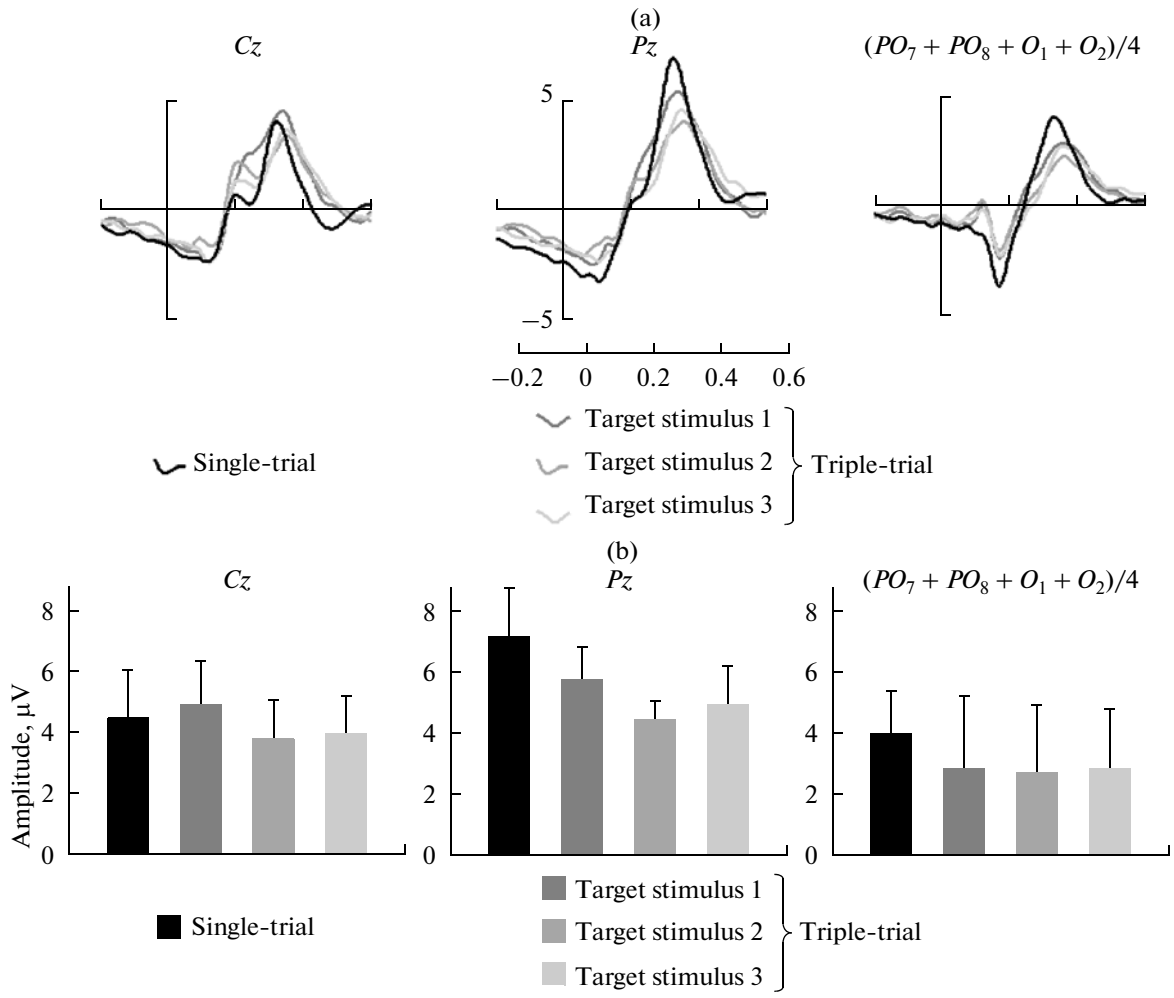

Fig. 2. Comparison of the ERPs in response to a target stimulus during single-trial presentation (group '1') and to each target stimulus during triple-trial presentation (group '3'). (a) ERPs at the *Cz* and the *Pz* electrodes and averaged occipital electrodes. Start of stimulus presentation corresponds to 0 ms on the time axis. Abscissa: time, ms. (b) Amplitudes of the *P*300 peak and *N*1 modulo in the same electrodes. Data are presented as means of four sessions. Ordinate: amplitude, μV. Number of subjects in each group for *N*1, $n = 6$ and for *P*300, $n = 5$.

less than 200 ms with other topographical and functional features was observed. This phenomenon is observed in the *P*300-based BCI in some healthy subjects and patients [11].

The *P*300 amplitudes of the ERPs to the target stimuli averaged for all sessions did not differ between the groups with triple-trial (group '3', average of three target stimuli) and single-trial (group '1') stimulus presentations at the *Cz* electrode according to the unpaired Student's *t*-test ($t(8) = 0.20$, $p = 0.8$). However, the *P*300 amplitude was higher by 2 μV in group '1' at the *Pz* electrode according to the unpaired Student's (*t*-test ($t(8) = 2.55$, $p = 0.03$). We analyzed the ERPs evoked by the first, second or third target stimulus presentations in the triple-trial stimulation mode. According to the paired Student's *t*-test, the *P*300 amplitude was higher for the first target stimulus compared to the second and third target stimuli by approximately 1 μV at the *Cz* electrode ($t(4) = 4.96$, $p = 0.008$ and $t(4) = 5.80$, $p = 0.004$, respectively) and at the *Pz* electrode ($t(4) = 3.14$, $p = 0.03$ and $t(4) = 2.42$, $p = 0.07$, respectively). The *N*1 amplitude was higher in group '1' as compared to group '3', but this effect was nonsignificant ($t(10) = 1.13$, $p = 0.28$), and did not differ between averaged responses to consecutive presentations of the target stimuli in group '3' ($p > 0.5$).

The accuracy of the choice of the target ball made by the subject using the BCI was 52, 54, 49, and 52% in sessions 1–4, respectively, in group '1' and 74, 74, 72, and 76% in sessions 1–4, respectively, in group '3'. The random level was 11%, because only one ball of nine could be chosen. According to ANOVA, the difference between the groups was significant ($F(1, 10) = 11.0$, $p = 0.008$), whereas the effect of the factor "session" and its interaction with the factor "group" were nonsignificant ($\lambda(3, 8) = 0.81$, $p = 0.6$ and ($\lambda(3, 8) = 0.92$, $p = 0.9$, respectively). Thus, we combined data from a different session for the next analysis (Fig. 3).

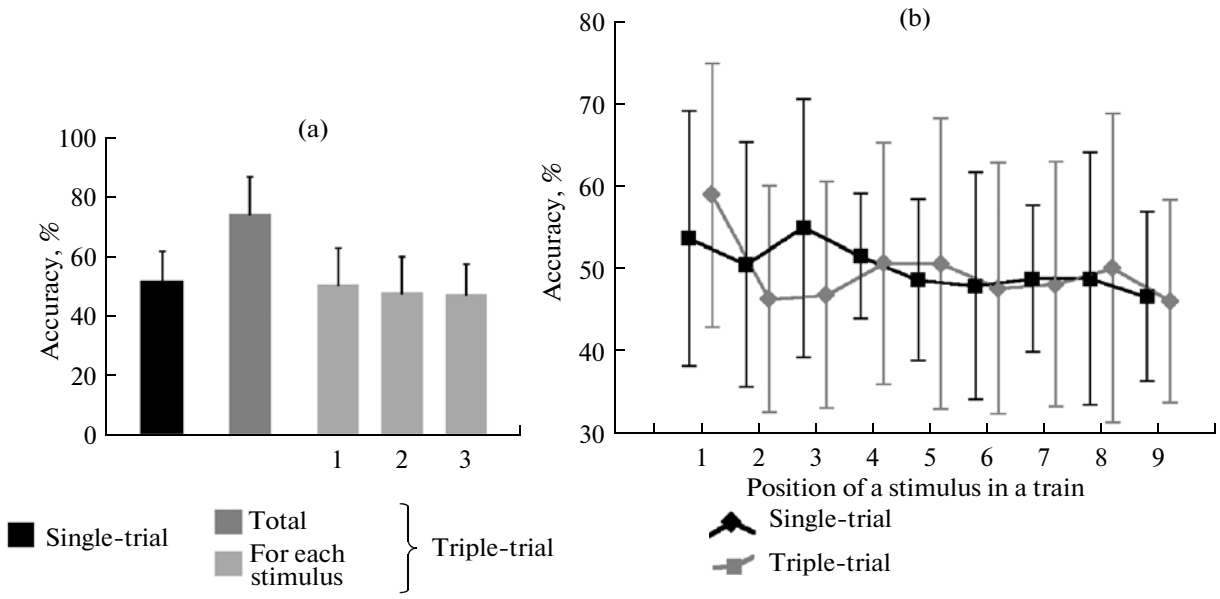

Fig. 3. Dependence of accuracy of control of the brain-computer interface in the experiment with a small number of stimulus presentations on a position of target stimulus. Accuracy was calculated for all four sessions as a ratio of the number of successful attempts of choice of target ball to the total number of attempts. Data are presented as mean and standard deviation. (a) Accuracy of choice during single-trial presentation (group '1', $n = 6$) and, in total, during triple-trial presentation (group '3', $n = 6$); (b) accuracy of choice calculated separately for presentations of target stimuli in various positions, from 1 to 9, in a train of non-target stimuli. During single-trial presentation (group 1, $n = 6$), all data were analyzed whereas, during triple-trial presentation (group 3, $n = 6$), only data for the first presentation of each stimulus were analyzed.

The classification accuracy was calculated offline using nonaveraged data for each target stimulus separately in the experiment with triple-trial presentation. This offline procedure is analogous to a subject's choice of a target ball using BCI with the single-trial presentation (Fig. 3a). We found that the accuracy was 50, 48, and 47% for the first, second, and third stimulus presentations; however, these differences were nonsignificant according to the paired Student's test ($p > 0.3$) and did not differ from accuracy during the single-trial presentation according to the unpaired Student's test ($p > 0.5$).

The effect of the position of the target stimulus in a stimulus train is of special interest. However, the amount of data for each position was insufficient for ERP analysis even after combining the data for all four sessions. Therefore, we analyzed the offline classification accuracy only. The accuracy for various positions of a target stimulus during the single-trial presentation varied between 46 and 55%. In the experiment with triple-trial presentation, the accuracy in the first stimulus train, i.e., upon the first presentation of each stimulus, varied between 46 and 59% (Fig. 3b). Combining the data for positions 3–7 and comparing these data with those for positions 1 and 9, i.e., the first and last, demonstrated that the effect of the factor "position" was significant ($\lambda(2, 9) = 0.45$, $p = 0.03$). The detailed analysis applied to the data for all positions, i.e., with nine levels of the factor "position", did not reach the level of significance ($\lambda(8, 3) = 0.10$, $p = 0.17$). The paired t-test applied to pairs consisting of the first position and one of the other positions demonstrated significant differences ($p<0.05$) for all pairs except those consisting of the fourth and fifth positions in the protocol with triple-trial presentation only.

DISCUSSION

In this study we analyzed, for the first time, features of the ERPs evoked by the first presentation of a stimulus in the *P*300-based BCI. We found that the amplitude of the *N*1 component with the occipital (mostly lateral-occipital) location and a latency of about 200 ms was approximately 1.5 times higher in the response to the first stimulus in the standard matrix protocol for the *P*300-based BCI compared to later stimuli (Fig. 1). The amplitude of the *P*300 wave at the *Pz* electrode, where it was the most distinct, did not decrease under the same conditions.

Using a small number of stimulus presentations in our modification of the *P*300-based BCI with moving stimulus positions, we did not reveal any significant differences of the *N*1 amplitudes in the responses to the first, second, or third stimulus presentation, as well as between the protocols with single-trial or triple-trial presentation. On the contrary, the *P*300 amplitude in response to the first stimulus was significantly higher compared to the second and third stimuli. Furthermore, at the *Pz* electrode, the *P*300 amplitude was maximal during single-trial presentation (Fig. 2).

Taken together, our data are in accordance with the data in the literature on the decreases in the ERP components' amplitudes to consecutive stimulus presentation [14, 15]. However, this effect is observed not in all conditions (e.g., [27]). Therefore, its presence and capacity could not be estimated for specific conditions of the *P*300-based BCI without additional experiments. The fact that the amplitudes of some ERP components in the response to the first stimulus were only one-third higher to 1.5 times higher as compared to the responses to the other consecutive stimuli demonstrates that these effects cannot substantially influence interface operation under conditions of the *P*300-based BCI studied. This conclusion may be confirmed by the data on the classification accuracy, which was not improved in association with an increase in the amplitudes of potentials. However, it should be taken into account that usually the BCI classifier is tuned to recognize ERPs according to their amplitudes and does not consider any other features, such as the pattern and topography, which results in a decrease in its efficiency during the presentation of a small number of stimuli.

Special attention should be paid to the possible dependence of ERP on the position of the target stimulus in a train of nontarget stimuli when a small number of stimuli are used for averaging. In our experiments, this dependence was expressed as the corresponding dependence of the classification accuracy (Fig. 3b). However, the statistical significance of this effect was relatively low ($p = 0.03$ without correction for multiple comparisons), and additional study involving a larger number of subjects is necessary.

In experiments with ten or three presentations of the target stimulus, the presentation of the last target stimulus was associated with a higher *P*300 amplitude (Figs. 1, 2) compared to the responses to stimuli in the middle of a train. This effect was nonsignificant; however, it seems to be important that the effect corresponds to the rebound effect described in the psychophysiological literature, which is observed at the end of a block with a fixed number of stimuli. The rebound effect is probably related to an enhanced subjective importance of the last stimulus [14]. It is possible that, under specific conditions, this effect may be greater, and engineers have to take it into account during development of the *P*300-based BCI.

Single-trial presentation of stimulus in each experimental block was associated with a higher *P*300 amplitude of the ERP as compared to the responses to the first stimuli in the experiments with triple-trial presentation. This is probably because the subject responded to the first target stimulus in the single-trial paradigm with higher attention compared to the response to the first target stimulus in the triple-trial paradigm.

In conclusion, these data demonstrate the possibility to increase the efficiency of position-based BCIs using modified algorithms of recognition of target ERPs for their differential estimation in the responses to the first and subsequent target stimuli and, probably, taking into account topographical features of ERPs.

CONCLUSIONS

(1) In the standard *P*300-based BCI paradigm with ten presentations of the target stimulus, the amplitude of the occipital *N*1 ERP component in response to the first target stimulus was higher as compared to the responses to later target stimuli. We did not observe a decrease in the amplitude of the *P*300 component under these conditions.

(2) In the modified *P*300-based BCI paradigm with moving stimulus positions, triple-trial presentation of stimulus was associated with a higher amplitude of the *P*300 component in response to the first target stimulus compared to the responses to the second and third stimuli. The amplitude of the *P*300 component in response to single-trial presentation was higher compared to the responses to triple-trial presentation.

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