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Changes in the N200 and P300 Components of Event-Related Potentials on Variations in the Conditions of Attention in a Brain–Computer Interface System

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We put forward the hypothesis that the amplitudes of the P300 and N200 components of visual potentials evoked by flashes of the columns and rows of symbols in a matrix depend on the nature of the task attracting the operator's attention to target symbol stimuli: 1) simple observation of the flashes of the target symbol; 2) observation with counting the numbers of these flashes and monitoring the success of this operation; 3) observation of the flashes of the target symbol with display of the symbol on a screen when the subject's attention to this symbol was detected using the EEG as a brain–computer interface. Studies using a group of 17 subjects showed that the maximum amplitudes of the P300 and N200 components of visual potentials were reached to a statistically significant level in the second operator attention regime, which did not require involvement in a brain–computer interface. The second condition showed the largest number of statistically significant differences between the amplitudes of the P300 and N200 components of visual potentials evoked by flashes of target and nontarget symbols. At the same time, the smallest amplitudes of these components and the smallest differences between reactions to the target and nontarget stimuli were seen in conditions of simple observation of the flashes of the target stimuli. These results lead to the conclusion that successful operator functioning in a brain–computer interface does not require the maximal expression of the P300 and N200 components of visual potentials, which probably start to be optimized in the brain–computer interface in the task of controlling external processes, such as display of the target symbol on the computer screen.

Keywords: brain–computer interface, biocontrol, evoked potentials, P300, attention, human operators, N200.

Brain–computer interfaces (BCI) constitute a new paradigm in psychophysiology research, where concrete EEG parameters are transformed by a program into commands to control external devices. Thus, these external devices become subject to direct dynamic control by the brain to perform some specific function, such as displaying a text on a screen, moving a manipulator grabber in space, or make a paralyzed limb perform some specific movement using an EEG-controlled exoskeletal construct [Frolov et al., 2013; Vidal, 1977; Wolpaw, 1991]. Focusing attention on concrete external stimuli or internal images, the BCI user promotes the appearance at the EEG level of stimulus-specific EEG patterns, transforming them into command signals for communication and control without mediation by nerves and muscles [Wolpaw et al., 2002].

One of the first and to date most effective BCI is letter-by-letter text selection, controlled by the P300 wave of visual potentials [Farwell and Donchin, 1988]. This technology is based on the well-known oddball effect, where increases in the subject's attention to one stimulus are apparent as an increase in the P300 wave of event-related potentials (ERP) [Krusienski et al., 2008]. If a matrix of $n \times n$ symbols is displayed on a screen, flashing individually at different time points, a unique response with a maximal

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P300 wave amplitude indicating the symbol in the matrix attracting the operator's attention can be identified among the ERP to the flashes of each of these symbols [Ganin et al., 2012; Kaplan et al., 2013; Mikhailova et al., 2008].

The technology of "mental" selection of letters of the alphabet or command symbols on a control panel using a P300 BCI has good potential for exploitation, especially in medicine. In particular, such BCI communicators have allowed restoration of communication for patients with locked in syndrome, i.e., completely lacking the ability to execute any kind of muscle action. In addition, this technology provides the basis for developing BCI-controlled training systems, prostheses, and exoprostheses to restore or replace motor functions, for example, in poststroke patients or in invalids lacking limbs [Ortner et al., 2011; Piccione et al., 2006].

Recent studies have demonstrated that not only the P300 wave, which is linked with attention to target stimuli in humans, but also the N200 component of the ERP [Shishkin et al., 2009], the extent of which depends more on fixation of the gaze on the target stimulus than on the attraction of attention to it [Frenzel et al., 2011; Treder and Blankertz, 2013], makes a definite contribution to recognizing the interest of a human operator in one or another symbol in a BCI matrix. Therefore, when an operator is working with a BCI where the target stimulus is simultaneously the object of gaze fixation and selective attention, success in the algorithmic detection of the human's locus of interest in the symbol matrix may be better guaranteed if both ERP components are assessed.

However, because of differences in the neurophysiological mechanisms of these components of visual ERP, the extent to which the dynamics of the amplitudes of these components differ in different conditions of attracting operator attention to the target stimulus remains unclear; it is also unclear whether there are optimum conditions in which both components of evoked potentials (ERP) reach maximal amplitudes and generate the best discrimination of target from nontarget stimuli.

The aim of the present work was to perform a comparative analysis of the N200 and P300 components of visual ERP in BCI-P300 operators using three paradigms for attracting interest to the target stimulus: 1) observation of target stimulus flashing only; 2) observation of flashes plus counting the number of flashes during the session and monitoring the level of success of this activity; 3) observation of flashes of the target stimulus with each successful detection being displayed on a screen via EEG detection of the subject's focus of attention to the stimulus using a brain–computer interface (BCI).

Methods

A total of 17 subjects aged 18–30 years took part in the study. All provided signed informed consent to take part in the study after its aims and regulation had been explained. Each subject was asked to operate in three regimes. Identical stimulus conditions were used in all experimental series. A matrix of 36 cells was displayed on a computer screen, each cell containing a symbol (33 letters of the alphabet and three service commands) [Translator's note: there are 33 letters in the Russian alphabet]. Stimuli consisted of flashes of the rows and columns of the symbol matrix of duration 180 msec with 100-msec intervals between the end of one flash and the beginning of the next. Each column and each row flashed five times in random order in each stimulus cycle. Before each stimulation cycle, the subject reported which matrix symbol would be the target.

In each of the three operating regimes, the operator was told to work with nine stimulation cycles. Operator work regimes differed in the type of instructions given for working with the target stimuli and the presence of feedback during testing.

In the first regime (Watch), the subject had simply to observe the target stimulus specified by the experimenter in each test cycle and try not to be distracted by flashes of other symbols. The subject was not given any kind of success criteria when working to observe target stimuli.

In the second regime (Count), the stimulus regime was identical to that in the Watch regime, though the subject was required not only to observe the target stimulus, but also to count the number of flashes within each stimulation cycle. At the end of the stimulation cycle, the subject reported the number of target stimuli counted. At the end of the test session, the subject was told the overall results to allow them to see how their counts compared with the actual number of flashes of the corresponding symbols. Thus, subjects received some reinforcement of their work over nine cycles, though there was no operative feedback of the results of their work in each test cycle.

Sets of EEG traces in the Count test regime corresponding to episodes of flashing of the target and nontarget symbols were additionally used as a training set for construction of a mathematical classifier allowing EEG fragments belonging to one or another set to be discriminated. The classifier was constructed by Fisher linear discrimination (Krusienski et al., 2006], which allows the distance between the distributions of two different classes of objects to be determined. These object classes in our case were sets of ERP characteristics in response to the target and nontarget flashes using al EEG leads recorded (see below). The results of using the Fisher linear discriminant was a matrix of coefficients (the classifier), application of which to EEG data in the Print regime provided highly reliable extraction of those ERP which were linked with operator attention to the current target stimulus from the whole set of ERP.

The paradigm in the third regime (Print) was similar in the stimulus phase to the second regime, the only difference being that the subjects themselves specified the symbol whose flashes they would observe and count as target stimuli. Results of cycles of flashes obtained using a pre-prepared Fisher classifier were used for algorithm-based prediction of which stimulus was at the subject's center of attention. This

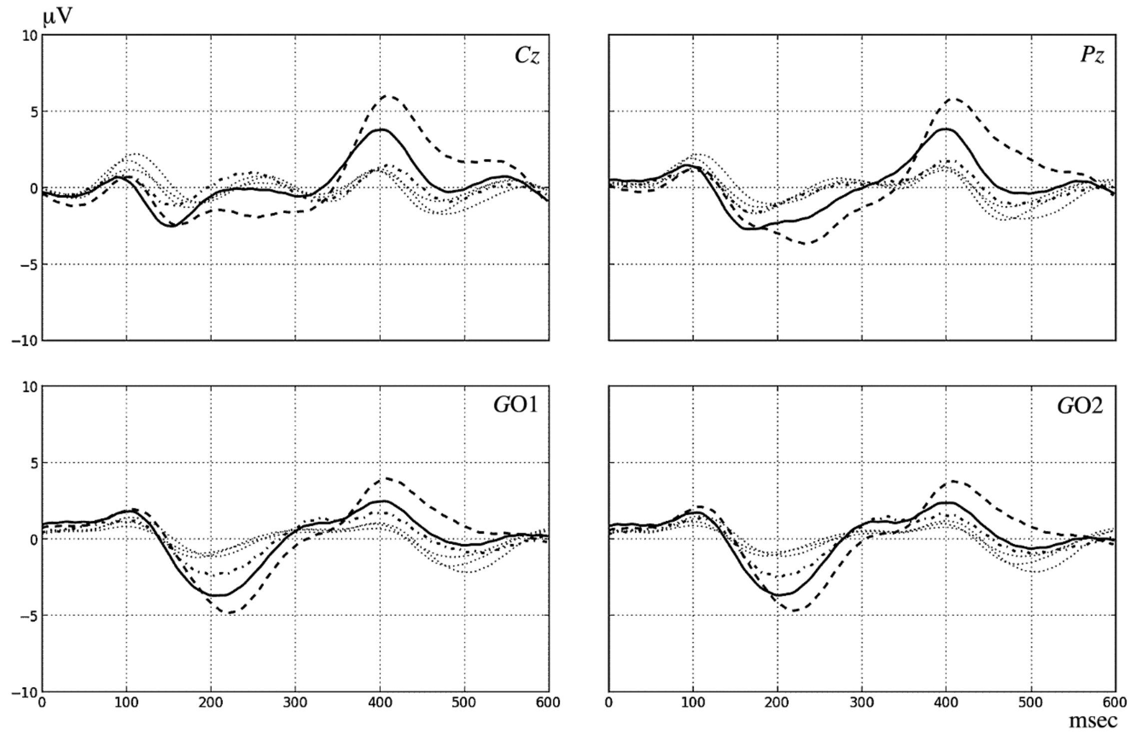

Fig. 1. Event-related potentials for different attention-attracting regimes averaged for the whole group of subjects. Subjects' operating regimes: dotted-dashed line – Watch; dashed line – Count; continuous line – Print. The abscissa shows time, msec, from the moment of stimulus presentation (flashing of column or row); the ordinate shows averaged ERP, μV. Images show leads *Cz* and *Pz* and the averaged occipital leads *GO1* and *GO2*.

symbol was displayed on the screen in a control text line. Thus, working letter by letter, the subject could select a text as desired. All subjects were asked to select the same word: "research" [Translator's note: the Russian word specified is: *issledovanie*]. In this regime, subjects were presented with at least 12 (the number of letters in the test word) cycles of flashes of the matrix rows and columns. The stimulation parameters (angular sizes of matrix and symbols, intensity of flashes of symbols, durations of flashes and intervals between them, numbers of flashes) in this regime were optimized to ensure the highest level of operator accuracy in the BCI system. Generally, if subjects made any errors, they made no more than one when working with sets of test word letters.

Each subject worked in all three regimes. The Watch regime was always the first. The Count and Print regimes were used in random order: the Count regime was before the Print regime in nine subjects and after it in eight, with the Watch regime being followed by the Print regime and then the Count regime. In this last group of subjects, the Print regime was preceded by a session performed to construct the classifier, which was largely similar to the Count regime, though the subjects were not required to count the number of flashes and the duration of the session was about one third of that of Count regime.

EEG traces were recorded in eight leads: *Cz*, *Pz*, *O1*, *O2*, *PO3*, *PO4*, *PO7*, and *PO8*, with a signal digitization frequency of 500 Hz. Data were processed by filtration for the range 1–13 Hz (Butterworth filter, second-order filtration). The parietal-occipital leads were averaged (after filtration) because the signals were very similar, to produce two occipital groups: *O1*, *PO3*, and *PO7* into group *GO1*, and leads *O2*, *PO4*, and *PO8* into group *GO2*. The classifier was constructed using all these EEG leads individually.

P300 amplitudes in lead *Pz* and N200 in the averaged group *GO1* were analyzed in the different regimes. The maximum values of P300 was seen in the prefiltered EEG in lead *Pz* at 300–450 msec after each flash and the maximum N200 was seen at 100–270 msec in the averaged group *GO1*. The resulting amplitudes were then averaged relative to the target and nontarget flashes. These parameters were analyzed statistically both for groups overall and for individual subjects. For groups, significant differences were identified in target stimulus response P300 and N200 amplitudes between the different operator work regimes. Comparisons for individual subjects were not only between the different work regimes, as for the overall groups, but also for identifying significant differences in the amplitudes of potentials in response to individual target and nontarget symbols, which required calculation not only of the ampli-

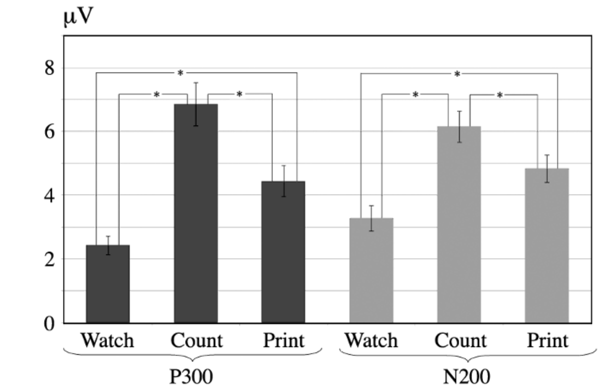

Fig. 2. Group average P300 and N200 amplitudes (μV) in responses to visual stimuli for each operating regime. *$p < 0.05$.

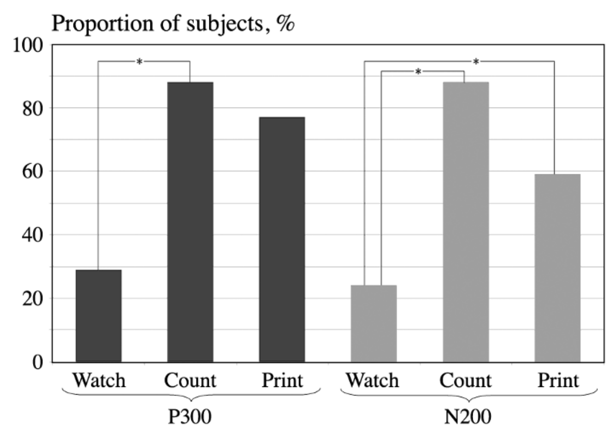

Fig. 3. Proportions of subjects (%) showing significant differences in the amplitudes of N200 and P300 potentials between target and nontarget stimuli for each operating regime. *$p < 0.05$.

tudes of components in averaged ERP, but also the amplitudes of individual peaks in the filtered EEG.

Data were analyzed using the open source environment Python 2.7.3 and statistical tests were run in Scientific Python (SciPy) 0.11.0.

Results

1. Comparison of group averaged peak amplitudes of P300 and N200 peaks to target stimuli for different stimulus matrix presentation regimes. The maximum amplitudes of both components, P300 and N200, in visual ERP taken as the group means for all subjects were statistically significant in conditions of observation of the target symbol with counting the number of flashes and subsequent control counts of the total number during the whole session (Fig. 1, Count). At the same time, the minimum amplitudes of these components were seen in conditions of observation of target stimuli without counting, and particularly with output to print in the BCI system.

It should be noted that in the Watch regime, in contrast to the other two regimes, there was virtually no P300 component in visual ERP. The responses to nontarget stimuli in all three regimes were similar (dotted line in Fig. 1).

As shown in Fig. 2, the group mean amplitudes of both components of visual ERP to target stimuli were statistically significantly different on pairwise comparison between regimes (Wilcoxon test, $p < 0.05$).

Attention is drawn to the fact that the amplitudes of the P300 and N200 components change, in the same direction and by essentially the same proportions, when the conditions for attracting attention to the target stimulus changed (Fig. 2).

2. Comparison of the amplitudes of the P300 and N200 components for target and nontarget stimuli in different stimulation matrix presentation regimes. Almost 90% of subjects demonstrated statistically significant differences in the P300 and N200 components for target and nontarget stimuli in the Count regime, while this was the case for 77% and 59%, respectively, in the Print regime (Fig. 3). At the same time, only 29% and 24% of subjects showed statistically significant differences between P300 and N200 amplitudes for target and nontarget stimuli in the Watch regime (Fig. 3).

As shown in Fig. 3, significant differences in the numbers of cases with reliable discrimination of the amplitudes of ERP components were seen only between the Watch and Count regimes (for N200 and P300); the N200 component showed significant discrimination between the Watch and Print regimes (Fisher's exact test, $p < 0.05$). Discrimination between the Count and Print regimes for both the N200 and P300 components were statistically insignificant.

Discussion

Both comparison of the absolute amplitudes of the P300 and N200 components for target stimuli in different regimes and comparison of the relative numbers of subjects showing statistically significant differences between target and nontarget stimuli in terms of both ERP components showed that maximal evaluations were obtained on behavioral testing in the Count regime and the minimal in the Watch regime (Figs. 2 and 3). However, all subjects successfully operated in the Print regime, i.e., in the BCI-P300 system, where letter selection accuracy by definition depended on how well differences in EEG responses to target and nontarget stimulation were detected. The results showed that this regime should display the largest differences in P300 and N200 for target and nontarget stimuli, as it was only in this regime that the differences seen operated as the command signal for execution of the operator's intent to select one letter or another.

This apparent non-correspondence between the data obtained and the expected result evidently demonstrates the fact that the fundamental factor for the differential detection of responses to target stimuli in the Print regime is neither the absolute amplitude nor the statistically significant difference in amplitudes for target and nontarget stimuli in specific pairs of EEG leads. The spatial pattern of ERP whose classification features were calculated using a recognition algorithm trained directly on training sets, for example, using the Fisher linear discriminant method, is important for the stable detection of these differences. Thus, transfer from the Count regime, where the result of behavioral discrimination of stimuli is the counting of points, to the Print regime, where this result becomes a command control, evidently produces drastic changes in the strategy of the cerebral mechanisms in generating responses to external stimuli, giving priority not so much to their amplitude in particular leads as to the stability of their spatial properties.

Another of the present results important for this discussion is the behavior of the P300 and N200 components going from one test regime to another, virtually identical, in relation to both the absolute amplitudes of the ERP components and the properties of the difference between the ERP components for target and nontarget stimuli. This parallelism in the dynamics of the P300 and N200 components of ERP on substitution of test regimes indicates that despite differences in the neurophysiological and psychophysical mechanisms underlying the generation of these ERP components, their extents were determined equally by a uniform behavioral task. This uniform behavioral task was the reliable extraction of the target stimulus, which in turn required displacement of the operator's focus of attention and gaze direction. According to published data, this double task produces synchronous changes in P300 and N200 amplitudes [Brunner et al., 2010; Frenzel et al., 2010; Treder and Blankertz, 2010].

Conclusions

1. Successful operator work in a BCI did not require maximal amplitudes for the P300 and N200 components of visual potentials in response to target and nontarget stimuli or their maximal discrimination in pairs of individual leads, but relies on a set of changes in these components in the same direction, which provides for reliable real-time detection of the locus of the operator's attention in related to the active symbol matrix.

2. Changes in the amplitudes of the N200 and P300 components of evoked potentials were in the same direction, which reflects the simultaneous nature of the processes underlying gaze fixation and the focusing of attention to target stimuli in the matrix using the BCI.

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