EEG Correlates of Decision-Making and Preparation of Saccades in Human

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***Abstract* - A modificated version of experimental scheme "double step" was used to study the decision-making process in saccade programming. Two short visual stimuli were presented sequentially in opposite hemifields (scheme pulse overshoot). The "pattern" of response (double saccade or single saccade at the second target) and latency of the first saccade depended on the duration of the first stimulus (150 or 50 ms). Positive ERP components were revealed within the interval 100 - 120 ms before the saccade onset by using the method of selective EEG averaging. These potentials can be considered as markers of the decision-making process. The parameters and topography of these components indicate involvement of the frontal-parietal neural network of saccadic control and frontal-parietal-and medial-thalamic activation systems of selective attention at the stage of decision-making process.**

Keywords the positive component; saccade programming, decision-making, event related potential (ERP).

I. INTRODUCTION

The nature of decision-making process as one of the major cognitive function remains still unclear. Saccadic eye movements as an elementary form of goal-directed behavior can serve as a model for studying the mechanisms of decision-making. The "double step" paradigm can be used to study this problem [1]. In this paradigm the "pattern"' of saccadic response (double saccades at both stimuli or single saccade at the second one) depends on the completion of "the decision-making stage " [2-4]. Previously only saccade parameters and its latency were studied in "double step" paradigm. We assume that the analysis of the local EEG potentials associated with an appearance of the first target or saccadic onset depending on the saccade "pattern" may provide information for the study of neurophysiological nature of decision-making.

According to some researchers the eye movements preparation and decision-making is reflected in positive potentials preceding the movement onset [5 - 8].

Objective: to study the saccades latency (LP) and parameters of positive ERP components in latency period, depending on the "pattern" of saccadic responses in "double step" paradigm.

II. MATERIAL AND METHOD

A. *Participants*

18 healthy subjects (aged 19 to 24 years) consented to participating in this study. All subjects were right-handers and had normal vision. Their electroencephalogram (EEG) was recorded from 24 monopolar channels by 10-20 system. Horizontal eye movements were recorded using bipolar electrooculogram (EOG). The study was approved by the ethic committee of the Lomonosov Moscow State University.

B. *Stimuli and Procedure*

Two short stimuli were sequentially presented to the subjects on the display at the distance 7 and 3 degrees (or vice versa - pulse-overshoot scheme) from the central fixation point in the opposite hemifield (fig.1). Duration of the first target was set either 150 or 50 ms (50% probability). The experiment consisted of 700 -1 000 experimental trials depending on subjects.

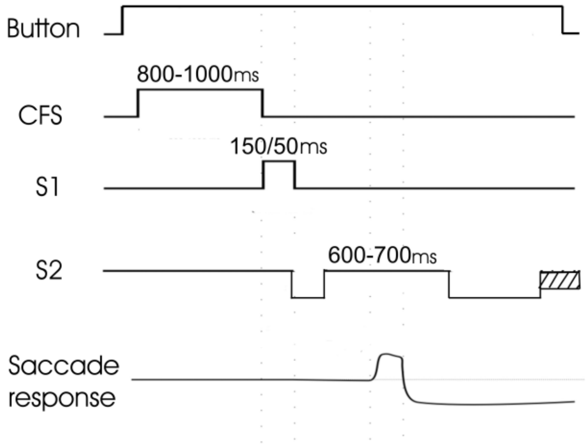

Fig. 1. Visual stimuli presentation at the "double step" experimental scheme. The shaded box means the second stimulus damping. CFS – central fixation stimulus, S1 –the first stimulus, S2 – the second stimulus.

C. *Data analysis*

A selective averaging method just before saccade, which latency was fluctuated in a narrow range of the main mode ±20 ms, was used to reveal local ERP components. An appearance of the first target (direct averaging) and the moment of the first saccade onset (backward averaging) were served as triggers. The number of averaged EEG epochs ranged from 20 to 30 depending on subjects. The amplitude, the pike latency and the topography of ERP components were calculated for the first target in the form of the P100 and P200 components and their appropriate analogues at the backward averaging - premotor potentials P -100 and P - 200.

Two-factor analysis of variance (saccade type ×

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number of subjects) was used for statistical analysis of LP. Factors studied were: the duration of the first target, ‘pattern’ of saccadic response and direction of saccades, each had two graduations. Nonparametric Wilcoxon test (W) and the frequency accordance criterion (Z) were used to check the data significance. ERP data were pooled at the absence of lateral differences in the ERP components.

III. RESULTS

A. Behavioral data

Saccade errors

Only 3 subjects made correct saccades, at the rest subjects the number of error responses ranged from 3 to 33% (24 ± 5%). For two subjects, the “double step” experimental scheme proved to be difficult to fulfill - they made more than 50% error answers including either – inaccurate, absent, or responses to the wrong direction.

Saccadic response “pattern”

We found variability in the “pattern” of saccadic response (double saccade or single saccade to the second target) and saccadic latency in different subjects. For three subjects only single saccade for the second target was observed, regardless of duration of the first target. In two subjects, the double saccade responses dominated, whereas single saccade occurred less than in 5-10% of the cases. Individual examples of saccadic ‘patterns’ of response are shown in figure 2.

We found significant difference in frequency of occurrence of single saccade to the second target compared with the double saccade responses in condition of 50 ms for the first target duration: 760 vs. 269 at the first target in the left hemifield and 651 vs. 348 at the first target in the right hemifield respectively (Z = 61.6, p = 0). Differences in the saccadic response “pattern” were not significant when the first target duration was 150 ms.

The dependence of the saccadic number and their latency on the first target duration, “pattern” of saccadic response and saccade direction also observed. Two-factor analysis of variance showed the influence of factor on the response in all compared cases ($p < 0.0001$).

Saccade latency

Latency of the single saccade to the second target was less than latency of the first saccade from the two at 49 ± 8 ms when the first target was 150 ms (W = 3.65 • 105, p = 0.03). This difference changed to the opposite when the first target lasted 50 ms - latency of the single saccade to the second target was larger than latency of the first saccade from two at 54 ± 22 ms (W = 1.76 • 105, p = 0.0003). Latency of single saccades to the second target was at 76.1 ± 8.7 ms less at the first target 150 ms compare to the first target 50 ms.

In 7 subjects who made many single saccades to the second target in 46 ± 8% of cases their LP ranged from 85 to 140 ms, which corresponds to express-saccades latency [4, 2]. In one subject all single saccades had express latencies ranged about 114.5 ± 0.9 ms for the first 150 ms duration target.

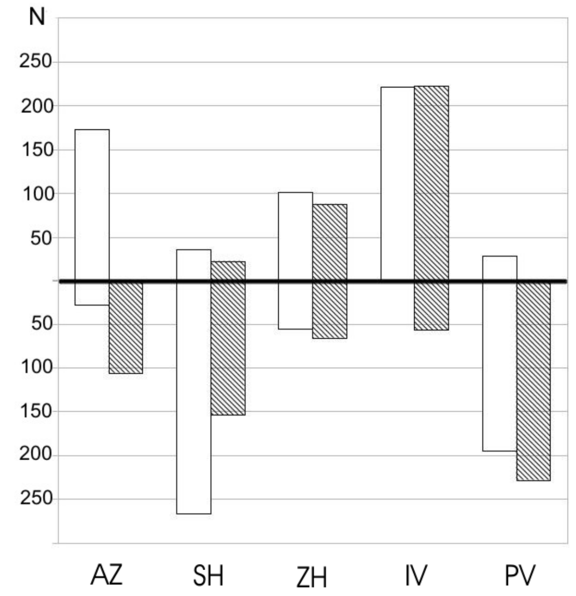

Fig. 2. Individual examples of the ‘pattern’ of saccade responses in subjects AZ, SH, ZH, IV and PV. N – the number of saccade responses. The columns above the *x*-axis denote the number of double saccade responses, the columns under the *x*-axis denote the number of the single saccade responses. White columns denote the 150ms duration of the first target, shaded columns denote the 50 ms duration of the first target.

B. ERP data

ERP analysis was performed in 12 subjects produced the sufficient number of saccades without artifacts. Positive P100 and P200 ERP components and their corresponding premotor components, which latency were depended on the saccadic LP, were studied (fig.3).

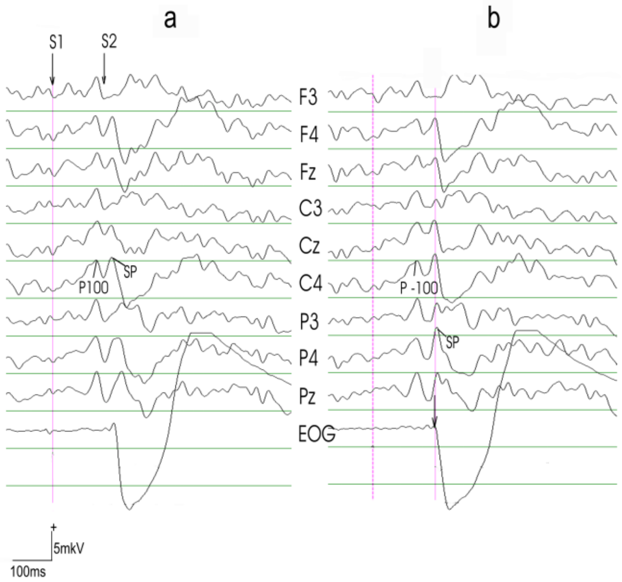

Fig. 3. Averaged EEG potential prior to the double saccade response in subject VD. a – direct averaging from the first stimulus onset (S1 arrow). S2 arrow –the second stimulus. S1 was in the left hemifield, S2 - in the right one. S1 duration - 150ms. b – backward averaging from the saccade onset (arrow on the EOG channel). Number of EEG averaging - 25.

The P100 component

Peak latency and amplitude

The mean value of the P100 latency was 115.1 ± 1 ms and at various subjects ranged from 109 ± 5 to 120 ± 3 ms. Latency of the P100 didn't depend on the "pattern" of saccadic response. Amplitude of the P100 ranged from 2 to 10mkV depends on subject. We also observed a significant increase in the P100 amplitude at the double saccade response, compared with a single saccade, regardless of the first target duration: 5.06 ± 0.6 and 3.6 ± 0.3mkV respectively (W = 404, p = 0.029).

The P100 component scalp localization

Maximum of the P100 peak amplitude was observed in the frontal, parietal, central or lateral and medial areas depending on subject. At the double saccade response peaks of the P100 component were localized more often in the contralateral to the saccade direction areas compared with ipsilateral ones: 7:2 respectively (Z = 2.828, p = 0.0047). For the single saccade to the second target the lateral differences in the P100 peak localization were not found.

To reveal a spatial-temporal dynamics of P100, we mapped its distribution every 10ms. We found that P100 had multiple foci in the frontal, central and parietal areas of one or both hemispheres. At the P100 development its foci shifted from one hemisphere to another and from anterior to posterior zones (or vice versa). In 84% of cases P100 foci localized in the medial areas ($Z = -6.746$, $p = 1.57 \cdot 10^{-11}$).

The P200 component

Peak latency and amplitude of the P200

The P200 component frequently appeared at the background of the second stimulus or after its ending if the saccade latency duration was more than 300ms. In case of double saccade response, the P200 component corresponded to the spike potential (SP) coincided with the onset of the first saccade in half of the cases, and it was excluded from the analysis.

The P200 latency ranged from 150 to 184 ms at the double saccade response and from 166 to 250 ms at the single saccade response. At the single saccade response the average P200 latencies were longer than at the double saccade response: 209 ± 6.1 and 185 ± 5.4 ms respectively (Fig. 4) (W = 250, p = 0.0076).

Regardless of the saccadic response "pattern" the P200 latency didn't depend on the first target duration. At the double saccade response the P200 latency was 185.1 ± 5 ms for the 150 ms target and 185.3 ± 6 ms for the 50 ms target, and for the single saccade response: 204.7 ± 5 and 204.5 ± 8 respectively.

The individual P200 amplitude ranged from 3 to 12 mkV. The average P200 amplitude was - 5.5 ± 0.23mkV in all subjects.

The P200 component scalp localization

As well as the P100 component the P200 peak amplitudes were more often localized at the lateral and medial frontal, parietal or central areas depending on subjects. For the single saccade response the peaks of maximum amplitude more often localized in the central and medial parietal areas (CPz and Pz), than in the lateral ones (26:15, Z = 2,211, p = 0.027). Furthermore, at the single saccade response maximum of the P200 peak amplitude was observed more often in the contralateral to the saccade direction areas as compared with ipsilateral ones 18:8 (Z = 3,051, p = 0.002).

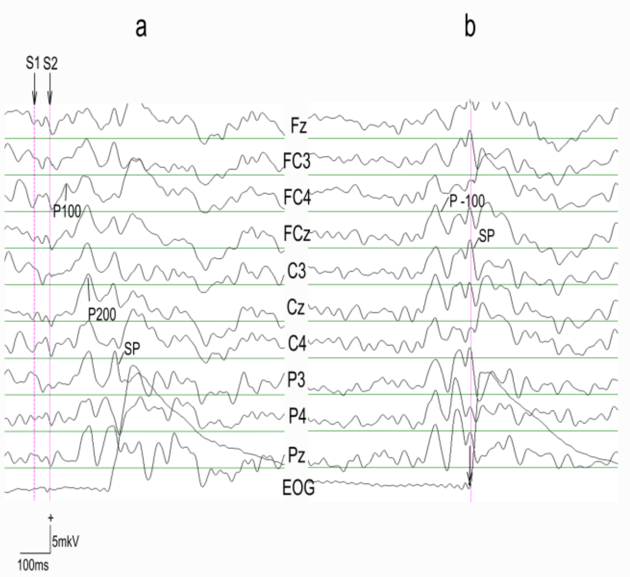

Fig. 4. Averaged EEG potential prior to the single saccade response in subject VD. a – direct averaging from the first stimulus onset (S1 arrow). S2 arrow –second stimulus. S1 was in the left hemifield, S2 - in the right one. S1 duration - 50ms. b – backward averaging from the saccade onset (arrow on the EOG channel). Number of EEG averaging - 26.

At the single saccade response the P200 peak amplitude was significantly larger in contrast with the P100 (amplitude): 6.0 ± 0.4 and 3.6 ± 0.3 respectively ($W = 519$, $p = 2.42 \cdot 10^{-6}$).

EEG mapping showed that the P200 as well as the P100 component have multiple foci in the frontal, parietal and central areas of one or both hemispheres and in the appropriate areas of the medial cortex. During dynamic mapping of the P200 peak amplitude its foci more often moved from frontal and central areas to parietal ones regardless of the response type (Z = -2,163, p = 0,03059). In most cases the P200 foci dominated in the contralateral areas (44:18, Z = -4,849, $p = 1{,}26 \cdot 10^{-6}$).

Premotor analogs of the P100 and P200 components

At the backward averaging from saccade onset the peak latency of the P -100 premotor component depended on the saccadic LP and ranged from - 40 to - 140 ms for double saccade and from - 80 to – 270 ms for single saccade to the second target (Figure 4). At the double saccade response latency of the P -100 was significantly smaller as compared to the single saccade response: 73.5 ± 10.1 ms and 165.9 ± 11.1 ms, respectively (W = 101, $p = 1.9 \cdot 10^{-5}$).

The peak latency of P200 premotor analogue ranged from - 68 to 108 ms at the double saccade response, and from - 52 to 144 ms at the single saccade to the second target response. This potential corresponded to the P-100 component as well as for the P100. At the double saccade response its latency was significantly shorter than at the single saccade response: - 80.7 ± 5.9 and - 102.2 ± 6.4 ms, respectively (W = 48, p = 0.028).

Significant differences in the P200 amplitude at the direct and backward averaging were not observed in all experimental conditions (5.4 ± 0.3 and 5.1 ± 0.4 mkV respectively).

As it was mentioned above, in seven subjects express - saccades were observed (with LP from 90 to 140 ms). Five of them produced the sufficient number of saccades for averaging without artifact. The P100 and the P200 peaks amplitude were higher at the backward averaging than at the direct one (from the first target onset) before express-saccades.: 5.1 ± 1.1 and 3.6 ± 12 ms respectively (W = 379.9, critical boundaries = 39-66). Significant differences in the peaks latencies of these potentials before express-saccades and regular saccades were not found.

IV. DISCUSSION

A. *Behavioral data*

Data analysis revealed the dependence of the saccades number to visual stimuli, the response pattern (double-saccade or single saccade to the second target) and saccade latency from the duration of the first target in the "double step" paradigm.

At the majority of subjects a significant increase in the number of single saccades to the second target when the first target duration was 50 ms compared with 150 ms was shown. These data correspond to the hypothesis of Becker and Jurgens that the full termination of the “decision-making” stage before onset of a second target is necessary for saccade initiation to the first target [3]. However, in some subjects the double step responses were observed within 50 ms of the first target duration. In terms of the model of “successive saccade programming” decision-making stage can’t be completed within the first 50 ms, because the processes of "disengagement of attention" from the fixation point [4] and the target valuation as the first step of decision-making [9] take place at this period. Our data suggest that a parallel programming of saccade as well as prediction of the target location, including the motor attention and the choice of motor program from memory before the second target onset, may take place at the "double step" paradigm [2].

This assumption is confirmed by decrease of the single saccade latency to the second target in comparison with latency of the first saccade from two saccades in case of the 150ms duration of the first target, and the appearance of express saccades in some subjects. In the psychophysiological literature express saccades are considered as markers of attention involvement in saccade programming [2, 4].

In 1979 Becker and Jurgens noted the appearance of the large number of single saccades to the second target in some subjects, and suggested that this fact reflects a specific strategy "to minimize muscular effort" and make saccade to the final target position [1]. This finding suggested an important role of the anticipation processes of motor response preparation in the experimental scheme "double step".

B. *ERP data*

Based on the hypothesis of Becker and Jurgens that a termination of the "decision-making" stage is necessary for the response on two short sequent stimuli in the paradigm of "double step" we assumed that method of selective EEG averaging let us to reveal differences in the ERP components to the onset of the first target in case of the double or single responses and thus to identify EEG markers of decision-making process.

We studied the ERP positive components P100 and P200 and their premotor analogues since these potentials correspond to previously described slow wave of premotor positivity occurring at 100-250 ms before the saccade. Early this potential was associated with processes of motor preparation, decision-making and movement initiation [5, 6, 8].

Using the "double step" paradigm in the ERP analysis is necessary to take into account the specifics of visual stimulation. The component P200 at the 150ms of the first target duration and the component P100 at the 50ms of the first target duration may reflect not only the motor preparation but also the early stage of sensory processing of the second target.

We have received a number of evidence that can associate the P100 and the P200 with decision-making stage. Firstly, the influence of the target duration on the peak latency and amplitude of the P100 and the P200 components regardless of the “pattern” of response was not found. This suggests that the sensor component has a weak contribution to the nature of these potentials as saccade.

At the backward averaging from saccade onset the peaks of premotor analogues of the P100 and the P200 correspond to the potential initiation the P -100. This potential has been studied previously in other saccadic paradigms, showed its connection with the processes of premotor preparation. [8, 10 - 12].

Second, the spatial-temporal dynamics of the P100 and the P200 with generalization of their foci on the cortex indicate activation of the frontal parietal distributed network of saccadic control, including the frontal, parietal and prefrontal oculomotor field (FEF, DLPF and PEF) [13, 14]. The prevalence of positivity foci in the medial areas (Fz, FCz, Cz, CPz and Pz) can reflect activating influence of the leading cortical structures in saccadic planning located on the medial surface of the frontal lobes (SEF and ACF areas – supplementary eye field and the anterior cingulated field) [13, 15], and the frontal-medial- and parietal-medial-thalamic systems of selective attention [16].

The contralateral dominance of the P100 and the P200 foci suggests an inclusion of directed attention in the decision-making and saccadic initiation stages [17]. Also this assumption is confirmed by the appearance of express-saccades in some subjects. In the psychophysiological literature express-saccades are considered as markers of attention involvement in the saccades programming. The nature of express-saccades is connected with the processes of "disengagement of attention" at the level of the striate cortex and superior colliculus [3, 4], or with processes of premotor preparation which start when saccadic system releases from fixation [18] or by motor anticipation mechanisms [11].

We showed the increase of the P100 amplitude at the double saccade response compared to the P100 at the single saccade response. In the single saccade response to the second target the P100 was observed in a range of 150 - 200 ms before the saccade onset and can reflect the "valuation stage" of the first target prior to "choice stage" at decision-making [19]. It can be assumed that decrease of the P100 amplitude at the single saccade response reflects a subthreshold level of the first target neural representation in the sensory and motor cortical maps that leads to the negative first target valuation as saccadic goal and "cancel" the decision about the first saccade initiation in favor of the second target.

Correlation of the P100 and the P200 latencies and their premotor analogue P -100 in the double saccade response compared with the single saccade may indicate an acceleration of saccadic programming allowing initiation of the double response. This may be due to fluctuation of the background level of cortical activation or processes of expectations and motor preparation in the eye fixation period.

V. CONCLUSION

It was concluded that the use of saccadic paradigms "double step" shows the dependence of the saccades number, saccadic latency and ERP parameters of the "pattern of response" (the single or double saccade). Positive ERP components at 100 - 120 ms before the saccade onset were revealed using the method of selective averaging EEG. Dependence of their parameters and the topography on “pattern” of saccadic response suggests that they may be considered as markers of decision-making process.

Both behavioral and ERP data indicate that the inclusion of attention processes at decision-making stage of saccade programming and point to the possible role of anticipation processes before the target turning on that affect the “pattern” of saccadic response. The obtained data are important for planning of studies of mechanisms underlying motor acts. We suggest that further analysis of the parameters and the topography of negative EEG potentials associated with the first target onset, and also slow negative waves at the period of target expectation depending on the “pattern” of saccadic response will provide new information about nature of the decision-making.

IV. ACKNOWLEDGMENT

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