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Learning-Related Dynamics of ERP Component Amplitudes When Assessing Visual Signal Duration

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Abstract

Introduction. Using a systemic-evolutionary approach, we studied the dynamics of the relationships between task performance and the amplitude characteristics of ERP components during skill learning and improvement. Learning and improvement were assessed individually for every study participant, in contrast to before–after studies or the uniform interleaving approach used in psychophysiology. A sliding window method was used to analyze covariances between performance and the amplitudes of nine ERP components identified during the signal duration assessment epoch. **Methods.** A psychophysical task of discriminating short time intervals was used. Study participants (N=28) were divided into groups of those who had not acquired the skill, those who had acquired the skill, those who had not improved the skill, and those who had improved the skill. Task performance was recorded as well as unipolar EEG recordings in 11 leads. **Results.** The relationship between ERP component amplitudes and task performance varied for different ERP components. Components with peaks corresponding to intervals before the presentation of the assessed signal, the early positive component, and the component before the end of the assessed signal were shown to be most closely associated with learning. Despite the greater amplitude of the components identified in the middle of the presentation of the assessed signal, the relationship between performance and the amplitudes of these components did not differ across the aforementioned groups of study participants. **Discussion.** The results are discussed in the context of how positive and negative ERP components are interpreted as markers of changes in stages (substages) of a behavioral act. It has been shown that different subjective methods for determining the substages of a behavior act can lead to the acquisition of a new skill with a certain degree of probability.

Keywords

systemic-evolutionary approach, learning, skill improvement, EEG, psychophysics, learning dynamics, Yes/No Test, event-related potentials (ERPs)

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Introduction

Learning issues and their relationship to the dynamics of brain activity during these processes are relevant in psychophysiology (Alexandrov, 2014). An important aspect is that in literature, the term "learning" often refers to different processes (Aleksandrov, 2006).

According to the systemic-evolutionary approach (Shvyrkov, 1995), the complex of individual experience elements (systems of a behavioral act) represents a systemic structure reflecting the history of an individual's interaction with the environment. The formation of a system in the systemogenesis process ensures increasing differentiation in the individual's interaction with the environment. The implementation of behavior, during which it can be changed, is associated with changes in inter-systemic relationships that, from the point of view of an external observer, as well as during learning, may appear as "an improvement in the implementation of behavior". Thus, from the perspective of the systemic-evolutionary approach, it is possible to distinguish two processes: systemogenesis (more associated with the learning process) and changes in inter-systemic relationships (more associated with the process of improving an existing skill).

Some studies have used neural recording and examined the structure of individual experience, demonstrating that the processes of systemogenesis and changes in inter-systemic relationships are distinct (Gorkin, 2021). The structure of individual experience can also be studied using EEG. Positive EEG oscillations are associated with an increase in the number of simultaneously actualizing individual experience systems (Gavrilov, 1987) and with an increase in the degree of concretization of the subject of behavior (Maksimova & Aleksandrov, 1987); negative oscillations are associated with a decrease in the number of simultaneously actualizing systems (Gavrilov, 1987) and with a decrease in the degree of concretization of the subject of behavior (Maksimova & Aleksandrov, 1987).

The problem of dynamic examination of learning processes and skill improvement with electroencephalographic methods has been raised relatively rarely. Although there are many classical studies on brain mechanisms subserving learning processes, most of them are based on experiments constructed with the "before and after" comparison principle (see, e.g., Poon, 1974; Stuss & Picton, 1978; Verleger et al., 1985, etc.) or on the arbitrary selection of uniform epochs of analysis (McAdam, 1966; Peters et al., 1977; Taylor, 1978; Donald, 1980; Rosler, 1981; Kecei et al., 2006; Jongsma et al., 2006). Moreover, the literature describes conflicting conclusions about the increase/decrease in component amplitudes during the learning process. In our opinion, this approach is not informative enough, since it does not take into account the procedural component of learning.

To study the dynamics of learning and improvement processes, we used the psychophysical task of discriminating short time intervals using the Yes/No Test. This is due to its ability to carry out a continuous (non-dichotomic) assessment of the learning results (Apanovich et al., 2022; 2024), which is relatively free of decision-making factors (Zabrodin et al., 1984), and to the fact that this task is characterized by a learning process that is pronounced in its effect (Skotnikova, 2003). Another advantage of the task of discriminating short time intervals is, apparently, the relatively weak representation of experience with this behavior in the structure of individual experience.

The *objective* of this study is to evaluate the dynamics of the amplitude characteristics of the ERP components that manifest themselves during learning the skill of discriminating the duration of visual signals.

Methods

Study participants

A total of 28 participants (7 males, 21 females) participated in the study. The subjects ranged from 18 to 45 years of age (mean age — 23.1 years; median age — 19 years;

standard deviation — 8.66 years). The age of the respondents was controlled because the literature suggests that the 18 to 45-year-old age group shows the greatest stability in performance in tasks involving estimation/reproduction/discrimination of time intervals (Lisenkova & Shpagonova, 2021).

Based on the performance indicators developed and described in our previous studies (see Apanovich et al., 2022; Apanovich et al., 2024), participants in the study were divided into the following four groups:

1. Those who had not acquired the skill — a group in which the study participants initially did not perform the task (their performance was not statistically different from 0) and did not acquire the skill during the experiment (they did not overcome the threshold of a non-random solution d' = 0.546).
2. Those who had acquired the skill — a group in which the study participants acquired the skill of task performance during the experiment (at the beginning of the experiment, their performance was not statistically different from 0, but then they exceeded the threshold of a non-random solution d' = 0.546).
3. Those who had not improved the skill — a group in which the study participants initially had high levels of task performance (non-random, i.e., above the level of a non-random solution d' = 0.546), but did not improve the skill during the experiment (they did not statistically significantly improve their initial result).
4. Those who had improved the skill — a group in which study participants initially had high levels of task performance (non-random, i.e., above the non-random solution level d' = 0.546) and improved their skill during the experiment (statistically significantly improved their initial score).

Procedure and study design

The experiment consisted of three tasks, but this article only examines the results of the main series (the third one). The first task involved distinguishing vertical and horizontal lines. After being presented with these lines, the participant had to press the corresponding keys on the keyboard with the index or ring finger of their dominant hand. This task was used to control the participant's response time. The second task, which we termed "sensitizing" (by "sensitizing" we mean the onset and cessation of neural activity, correlated with existing systems (Apanovich et al., 2022)) was used to distinguish this process from de novo learning. The parameters of this series replicated those of the main experimental task, but the participants had to discriminate not the duration of signal presentation, but their absolute sizes.

The third and main experimental task was a modified psychophysical Yes/No Test (Gusev et al., 1998; Zabrodin et al., 1984). The presentation was conducted using a special software, Visual Yes/No Test (developed by S. A. Karpov). Short time intervals were used as the assessed parameter (see below a description of one trial). This method, in our version of the experiment, consisted of 10 series, each containing 50 trials (the participant was not informed in advance of the number of series and trials to avoid anticipation). The break between the series was 1 minute, during which the participant was asked to sit with his eyes closed to reduce eye fatigue. The total time to complete this task was about 40 minutes.

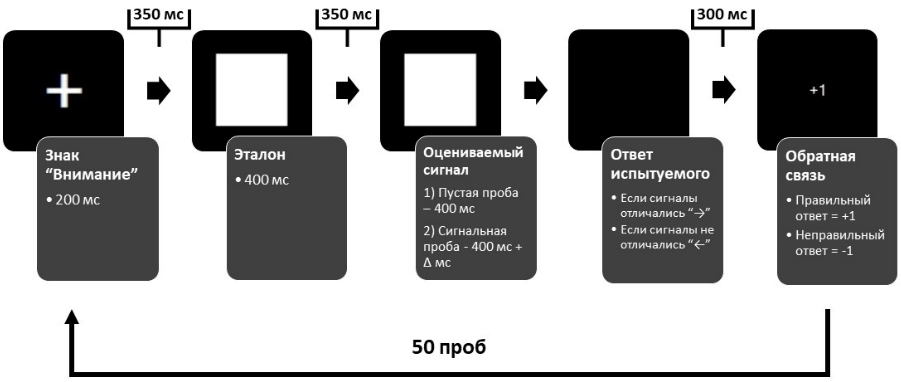
The first and second experimental tasks are control tasks for this experiment, and their results are not presented in this paper.

One trial description

Each trial began with the presentation of the Attention signal (white cross, presentation duration — 200 ms, 1x1 cm dimensions, RGB color combination: 183, 183, 183). After a 350 ms break (dark background, RGB: 0, 0, 0), a reference signal was displayed for 400 ms: a white square of 3x3 cm dimensions, RGB color combination – 183, 183, 183. Then, after a 350 ms break (dark background, RGB: 0, 0, 0), the signal to be assessed was shown. Its duration, with a 50% probability, coincided with the duration of the reference signal or exceeded the duration of the reference signal by a value predetermined by the scenario (either 66 ms or 92 ms longer, depending on the scenario selected for a particular study participant). Participants in the study were asked to press the "⊠" key with their index finger if they believed that the signal lasted longer than the reference signal, and the "⊠" key if they believed that the assessed signal lasted the same time as the reference signal. After responding, the participant received feedback on the accuracy of their answer ("+1" if the answer was correct and "-1" if the answer was incorrect). Figure 1 shows graphical representation of a trial.

Figure 1

Graphical representation of a trial (Apanovich et al., 2022).



EEG recording method

Recordings were made using non-polarizable silver chloride electrodes unipolarly in 11 leads: F3, Fz, F4, C3, Cz, C4, P3, Pz, P4, O1, and O2. Electrodes were placed according to the international 10–20 system. Two neutral electrodes were placed on the mastoids behind the ears. Two EOG electrodes for artifact detection were placed 1 cm from the outer corner of the right eye along the palpebral fissure axis and in the middle of the lower eyelid contour of the left eye. Contact resistance did not exceed 10 kOhm. The sampling rate was 250 Hz, the high pass filter was 70 Hz, the low pass filter was 0.1 Hz, and the notch filter was 50 Hz. The electroencephalograph-recorder model was Encephalan-EEGR-19/26. Rejection of oculomotor, muscular, technical, and other artifacts was performed manually using our proprietary EEGAnalyzer software (developed by S. A. Karpov).

Analysis epoch

The averaging epoch was defined as the interval from the end of the reference signal (350 ms before the onset of the assessed signal presentation) to the end of the assessed signal presentation (400 ms after the onset of the assessed signal presentation). The zero point was the onset of the assessed signal presentation. Thus, values from -350 ms to 0 ms corresponded to the interval between the reference and evaluation signals; 0 ms to 400 ms corresponded to the presentation interval of the assessed signal. This epoch was chosen because at that time the participant in the study estimated the duration of the signal presentation, i.e. performed the behavior that learning was studied in our study.

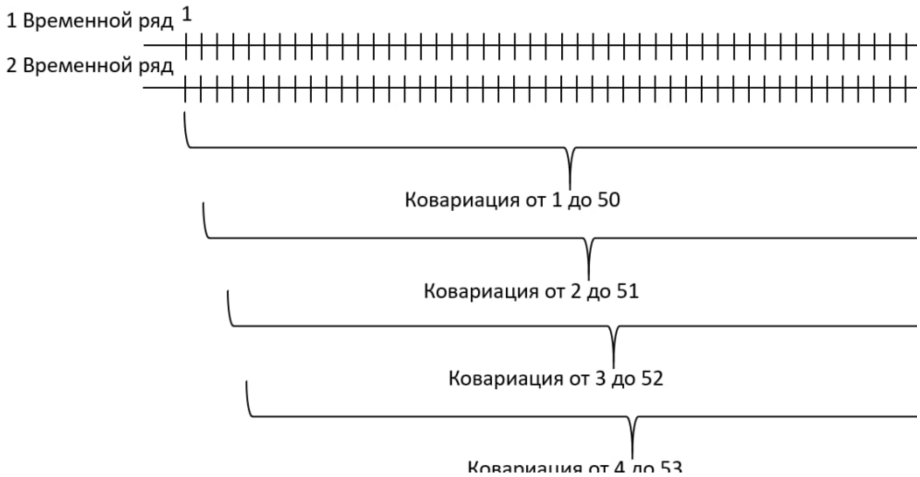
Variables analyzed and methods for obtaining them using the sliding window technique

To compare the learning process with brain mechanisms subserving the behavior of discriminating short-term intervals, we analyzed the decision indicator and amplitude (peak-to-peak) characteristics of the isolated ERP components (see the next section for the criteria for including components in the analysis).

To assess the *dynamics* of the relationships between performance and the amplitudes of event-related potentials (ERPs), a sliding window technique was used. For every participant, the d' indicator was calculated in intervals lasting 50 trials, and this window was then shifted in 1 trial (see Figure 2). Using the method described above, the amplitudes of the identified ERP components were averaged. Thus, after completing 500 trials, every participant had 451 d' values and 451 amplitude values for each of the identified components. These time series of 451 values showed the dynamics of the indicators during the series.

Figure 2

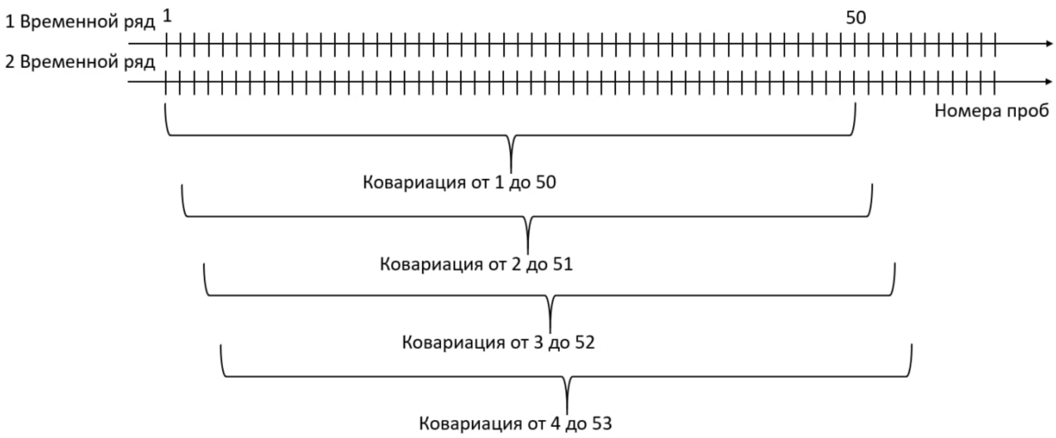
Illustration of the sliding window principle with a window size of 50 samples and a step size of 1 trial



The covariances between the two time series were calculated in a similar manner: The covariances were calculated over a window of 50 points obtained in the previous stage, also with a step size of 1 point (see Figure 3). Thus, two time series of 451 points yield a dynamic series of 402 covariances.

Figure 3

Illustration of the sliding window principle with a window size of 50 samples and a step size of 1 trial



For our analysis, we used the components described in the previous stage of the study (Yudakov et al., 2025). For the described epoch, the components presented in Table 1 were identified. Figure 4 shows an illustration of the model potential to describe the identified components. The moment of presentation of the assessed signal was considered as the zero point.

Table 1

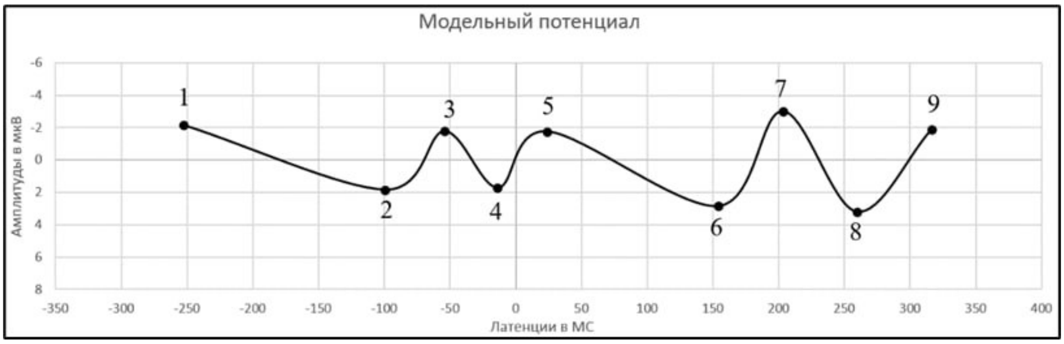
Amplitude-temporal characteristics of the identified ERP components in the analyzed epoch

Component	Average latent period, ms	Average amplitude, μV	Peak-to-peak amplitude, μV
1	-258	-2.13	–
2	-99	1.83	3.96
3	-55	-1.65	3.48
4	-15	1.78	3.43
5	22	-2.03	3.81
6	154	2.73	4.76
7	203	-3.06	5.79
8	259	3.21	6.27
9	313	-1.87	5.08

***Note**: The peak-to-peak amplitude is presented in each row relative to the previous component. Therefore, calculating the peak-to-peak amplitude for 1 component is not possible.*

Figure 4

Model potential of the identified ERP components in the analyzed epoch (Yudakov et al., 2025)



Identified intervals of covariance estimation for the groups of study participants

For every study participant, the relationship between the performance indicator d' and the amplitude of each identified component was estimated at each of the 451 points of the sliding window using the sliding covariance method. We divided the sequence of 451 averaging windows into the following epochs.

For the group of those who had acquired the skill:

- The epoch before crossing the non-random decision point d' = 0.546 ("before learning").
- The epoch corresponding to the performance increase during which the transition through the non-random decision point occurred – the interval between the local minimum preceding the increase and the local maximum after crossing the non-random decision point ("learning front").
- The epoch after crossing the non-random decision point ("after learning").

For the group of those who had improved the skill:

- The epoch before crossing the point reliably exceeding the initial performance ("before improvement").
- The epoch corresponding to the performance increase that crossed the point of reliable difference from the initial performance – the interval between the local minimum preceding the increase and the local maximum after crossing the point of non-random decision ("improvement front").
- The epoch after crossing the point of reliable difference from the initial performance ("after improvement").

For the groups of those who had not acquired and had not improved the skill, two epochs were identified to allow comparison with the groups in which the learning/improvement process was observed:

- The first half of the experiment.
- The second half of the experiment.

The values given in parentheses and quotation marks will be used hereinafter to denote the intervals described above.

Statistical methods for data processing

In the first stage, we sought to reduce the dimensionality of the leads. We also analyzed the consistency of the results obtained between the leads. Our previous studies demonstrated that brain mechanisms subserving the task of discriminating short time intervals are similar in the frontocentral and parietooccipital leads (Gladilin et al., 2025). However, this result was obtained without taking into account the dynamics and assessments of the relationships. To assess the consistency of the leads based on the relationship between performance and the amplitude characteristics of the analyzed components, we analyzed the standardized alpha coefficient.

To assess the dynamics of the relationship between performance and the amplitude characteristics of the ERP components, we conducted the following analysis, which included three stages:

(1) Evaluation of the difference between the average identified covariance and zero using a one-sample Student t-test (comparison of the average covariance value with a constant equal to zero). A covariance array was used for each of the selected intervals, and then a comparison was made to determine whether the distribution of covariances within each interval differed from zero. The analysis was conducted for every study participant separately.

(2) Comparison of covariances across intervals within the same group. For this, the covariances included in each array were used and compared with each other using the Student t-test. Thus, three pairwise comparisons were conducted for study participants from the groups of those who had acquired and had improved the skill (due to the selection of three intervals), and one pairwise comparison was conducted for the groups of those who had not acquired and had not improved the skill (comparison of the first and second halves of the experiment). The analysis was also conducted for every study participant separately.

(3) Comparison of the identified intervals between study participants from different groups. A matrix was formed that included the distributions of covariances across one of the intervals for all study participants from one group with all study participants in the other group. Similarly, pairwise comparisons were conducted between study participants from the selected groups.

The results obtained at the level of intra-individual comparisons were summarized in the context of their reproducibility and representativeness relative to the group as a whole, rather than to individual study participants. Due to the use of intra-individual comparisons, each result that characterizes groups and/or learning/improvement processes is associated with a distribution of importance levels, whose presentation would unnecessarily expand the scope of the article. Therefore, the results are presented in a generalized form.

Results were considered significant at a significance level of $p \leq 0.05$. We did not analyze the statistical trends.

Results

Based on the criteria described above, four groups of study participants were identified: those who had not acquired the skill (3 individuals), those who had acquired the skill (15 individuals), those who had not improved the skill (6 individuals), and those who had improved the skill (2 individuals). Two study participants were not assigned to any group because their performance indicators did not allow a final conclusion on their membership in one of the groups, i.e. they were in a "border position" and their assignment to a group could have been arbitrary. Participants whose EEG recordings contained artifacts were also excluded from the groups.

When comparing lead consistency, the similarity of mean covariance values was analyzed in the following three situations: identifying the fronto-central cluster, the parieto-occipital cluster, and combining all leads into a single cluster. Higher values of the standardized alpha coefficient indicate higher consistency among the leads included in a particular cluster. The analysis was conducted separately for each identified ERP component. Table 2 shows the results.

Table 2

Lead consistency indices when combined into different clusters using the standardized alpha coefficient

Component	Fronto-central cluster	Parieto-occipital cluster	Combining all leads into one cluster
1–2	0.91	0.94	0.96
2–3	0.90	0.88	0.94
3–4	0.90	0.88	0.94
4–5	0.89	0.81	0.92
5–6	0.88	0.77	0.92
6–7	0.83	0.92	0.94
7–8	0.90	0.92	0.95
8–9	0.89	0.92	0.95

***Note**: The maximum scores in the row are marked in bold.*

As can be seen from the table, the maximum consistency coefficients were obtained for all the extracted components when combining all leads into a single cluster. Therefore, the covariance indices across all leads were averaged and calculated as an integrated index. Unlike classical EEG averaging methods, such as General Potential, which average the EEG before preprocessing, our averaging was calculated from the covariance indices of the extracted peaks with the performance at each EEG lead. This avoids the typical shortcomings of traditional EEG averaging methods (e.g., the formation of "false" peaks that appear only when leads are combined, but do not appear at each lead individually).

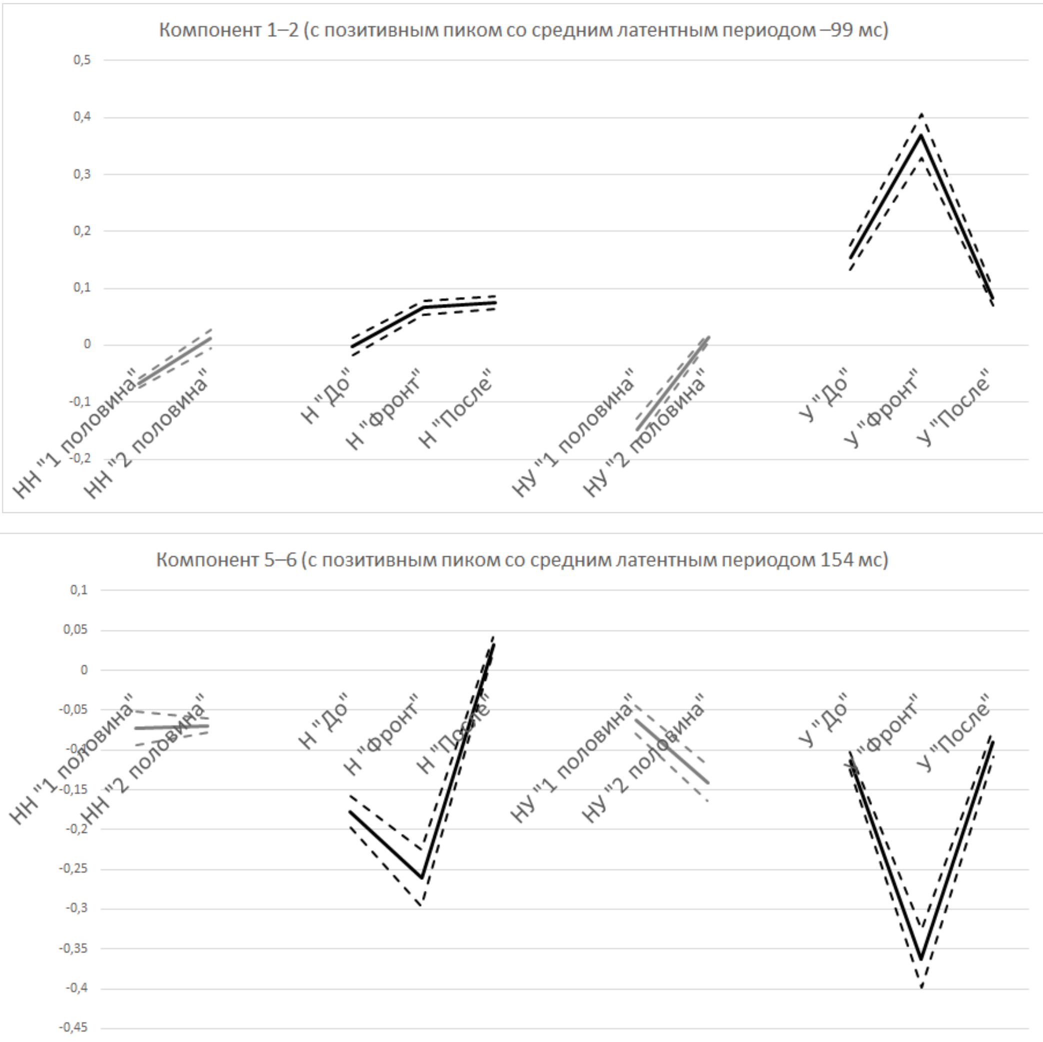
Analysis of the relationship between the ERP component amplitudes and performance for the identified components

It was shown that the amplitudes of different components have different dynamics of their relationship with performance indicators in different groups of study participants. The fragmentation of a behavioral act at a point in time coinciding with the positive/negative component is a marker of the systemic organization of the substages of the behavioral act in a particular participant, in which learning occurs with a higher/lower probability. Analysis of the relationship between the amplitudes of the identified components and performance allows us to divide the identified components into three conditional groups: "+" components — reflecting the occurrence of systemic processes that contribute to the effectiveness of learning; "-" components — reflecting the occurrence of systemic processes that do not contribute to effective learning; "0" components — the severity of which is not associated with learning.

The "+" group of components includes positive components 1–2 (with an average latency of -99 ms) and 5–6 (with an average latency of 154 ms). For a graphical representation of the relationships among individual study participants, see Figure 5. Participants in groups of those who had acquired the skill were characterized by a transition from an absent (component 1–2) or inverse (component 5–6) relationship between amplitudes and performance during the learning process; in this case, maximum scores are observed either during the learning process or after passing the non-random decision point. Participants in groups of those who had not acquired and had not improved the skill were characterized by either an inverse or absent relationship throughout the experiment. In other words, as performance increases, the amplitudes of these components begin to decrease (a tendency toward component reduction is noted). With respect to component 1–2, we should also note that the group of those who had improved the skill had higher covariance values in all three epochs than all the epochs of all the other groups. For an illustration of the dynamics of amplitudes and performance in the group of those who had acquired the skill, see Figure 6, which shows the maximum synchrony in increasing performance and component amplitudes during the learning period.

Figure 5

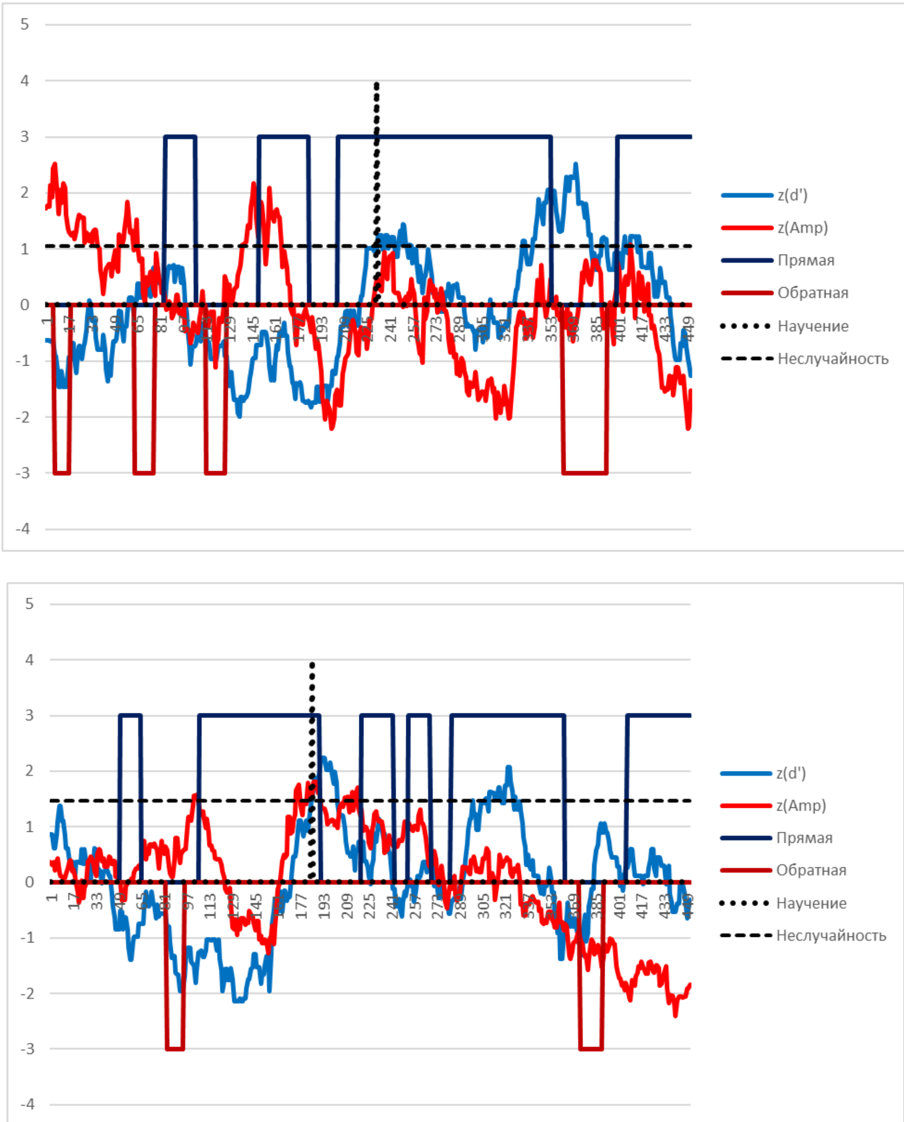
Dynamics of covariances between the amplitudes of the "+" group components and performance



***Note**: Data for individual study participants from 4 groups are shown (NA – those who had* **not** *acquired the skill; A – those who had acquired the skill; NI – those who had* **not** *improved the skill; I – those who had improved the skill). The solid line represents the mean covariance value within an epoch, and the dotted line represents the standard error of the mean. Values on the ordinate are given in μV.*

Figure 6

Dynamics of the relationship between the amplitudes of components 1–2 and 5–6 and performance



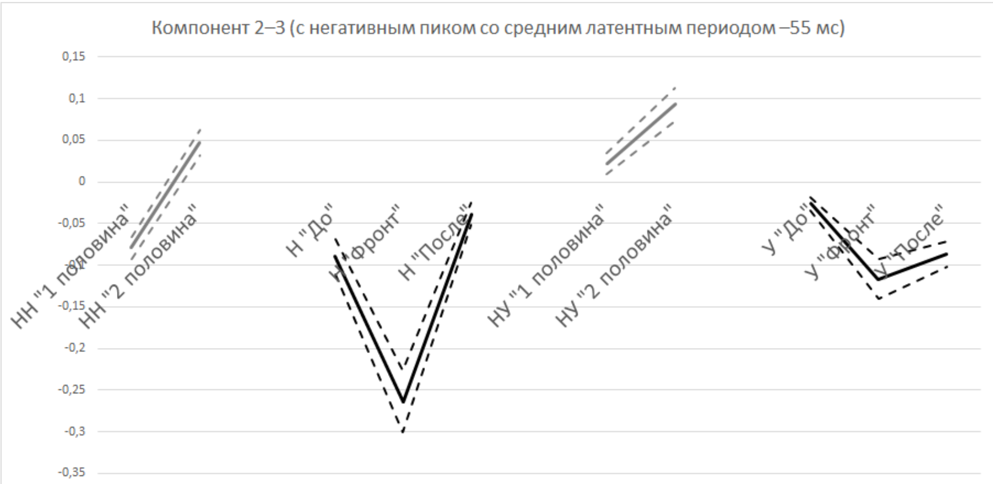
Note: *Performance dynamics are shown in blue, and amplitude dynamics are shown in red. Values are converted to z-coordinates to enable direct comparison. The vertical line indicates the moment the non-random decision point is crossed. Rectangular distributions indicate reliable direct (blue) or inverse (red) relationships. Data for individual study participants from the group of those who had acquired the skill are shown.*

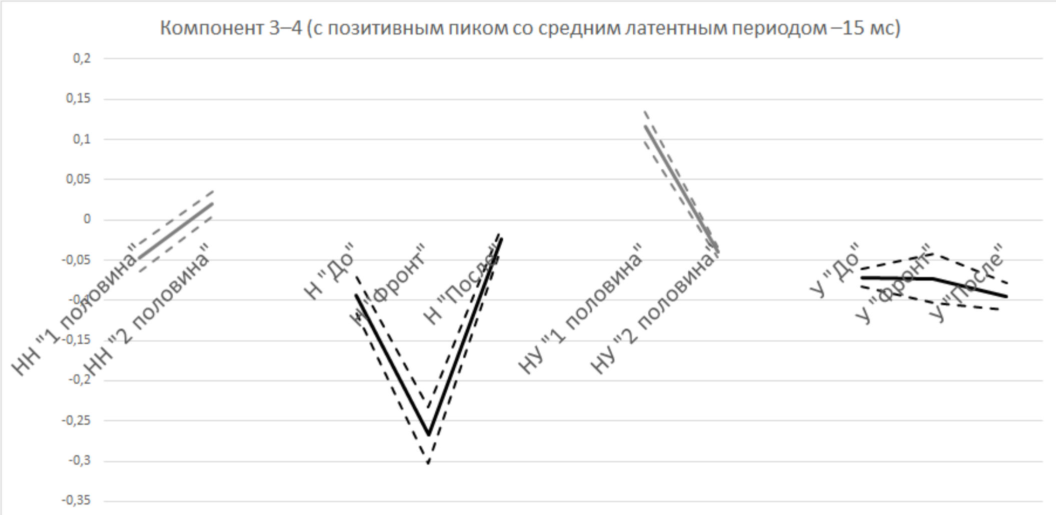
The "-" group components include lower-amplitude components: 2-3 (negative, with an average latency of -55 ms), 3-4 (positive, with an average latency of -15 ms);

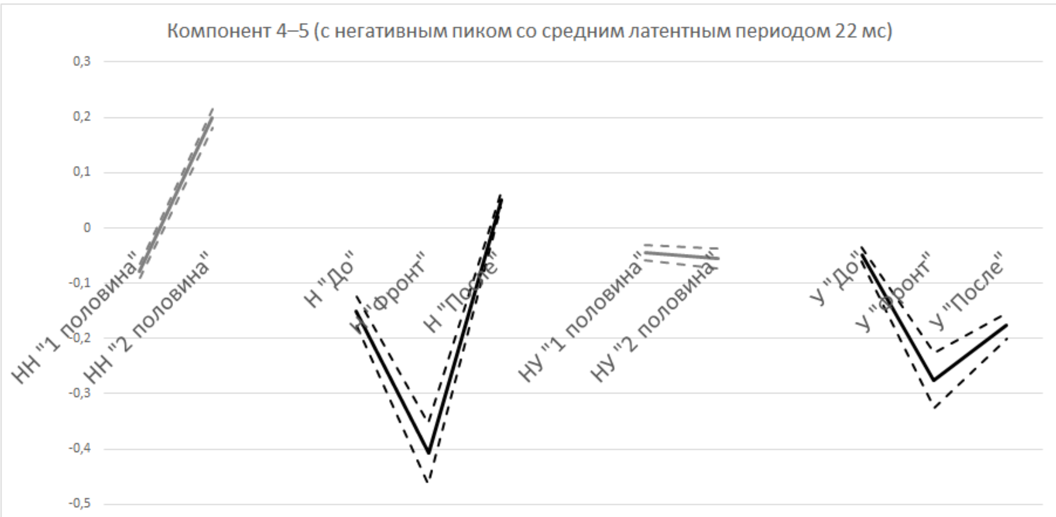
4-5 (negative, with an average latency of 22 ms). A graphical representation of the relationships for individual study participants is shown in Figure 7. It was shown that the group of those who had acquired the skill is characterized by an inverse relationship, which tends to be absent during the After Learning epoch. The strongest inverse relationship is observed in this group during the Learning Front epoch, i.e., during the active phase of increasing performance, these components are reduced. The groups of those who had not acquired the skill are characterized by a direct relationship in the second half of the experiment (negative components 2-3 and 4-5), while those who had not improved the skill are characterized by a direct relationship in the first half of the experiment (positive component 3-4) and generally higher covariances across all epochs compared to the group of those who had acquired the skill. Regarding component 4-5, we should also note that when comparing groups, there is a tendency for covariances to be higher in the groups of those who had not acquired and had not improved the skill compared to the group of those who acquired the skill. Thus, it can be concluded that the increase in amplitudes due to localized performance increases leads to the fact that, at the end of the experiment, the participants in these groups do not demonstrate reliable dynamics (learning/improvement).

Figure 7

Dynamics of covariances between the amplitudes of the "-" group components and performance







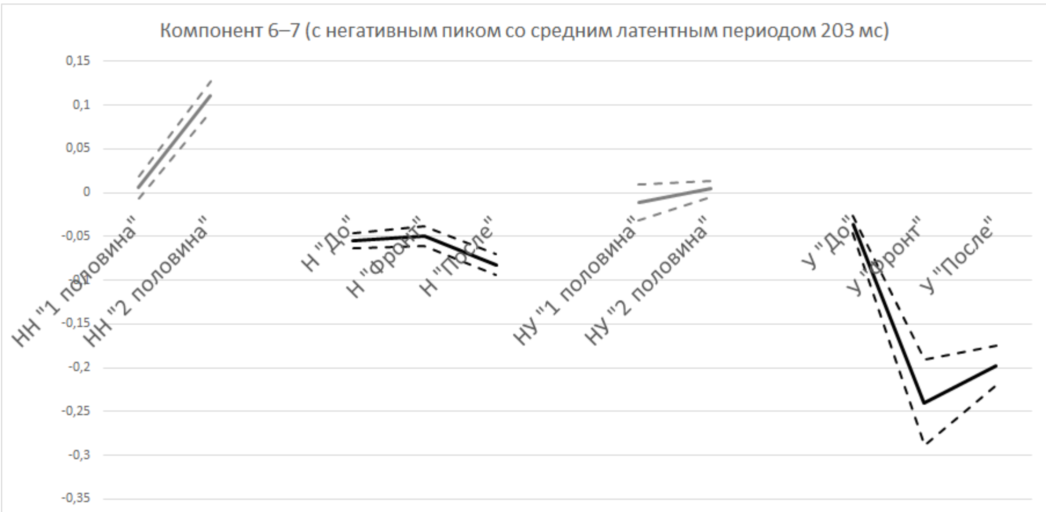
***Note**: Data for individual study participants from 4 groups are shown (NA – those who had* **not** *acquired the skill; A – those who had acquired the skill; NI – those who had* **not** *improved the skill; I – those who had improved the skill). The solid line represents the mean covariance value within an epoch, and the dotted line represents the standard error of the mean. Values on the ordinate are given in μV.*

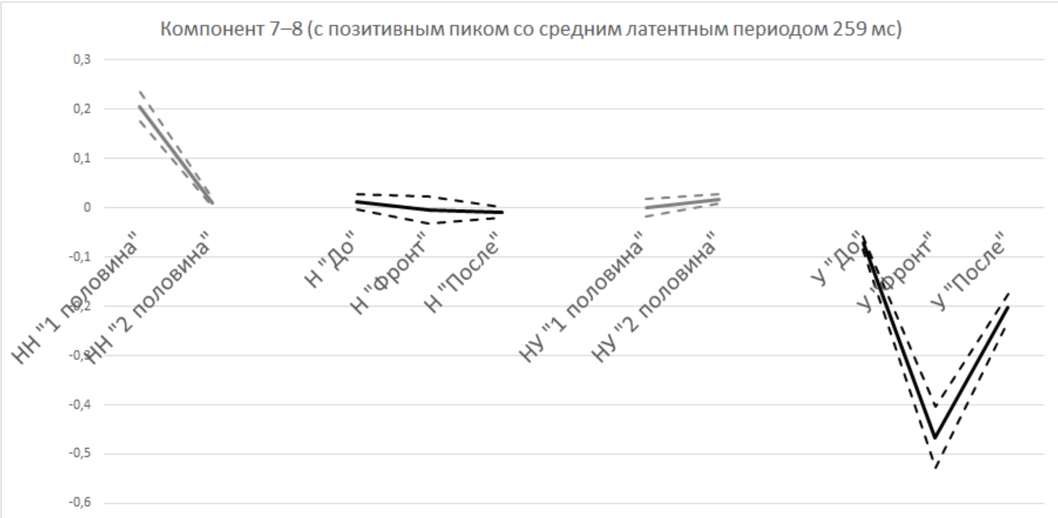
Group "0" includes the following components: 6-7 (negative, with a mean latency of 203 ms), 7-8 (positive, with a mean latency of 259 ms), and the later negative component 8-9 (with a mean latency of 313 ms). A graphical representation of the relationships for individual study participants is shown in Figure 8. Components 6-7 and 7-8 are the most stable and have the highest amplitudes, as shown in Figure 9.

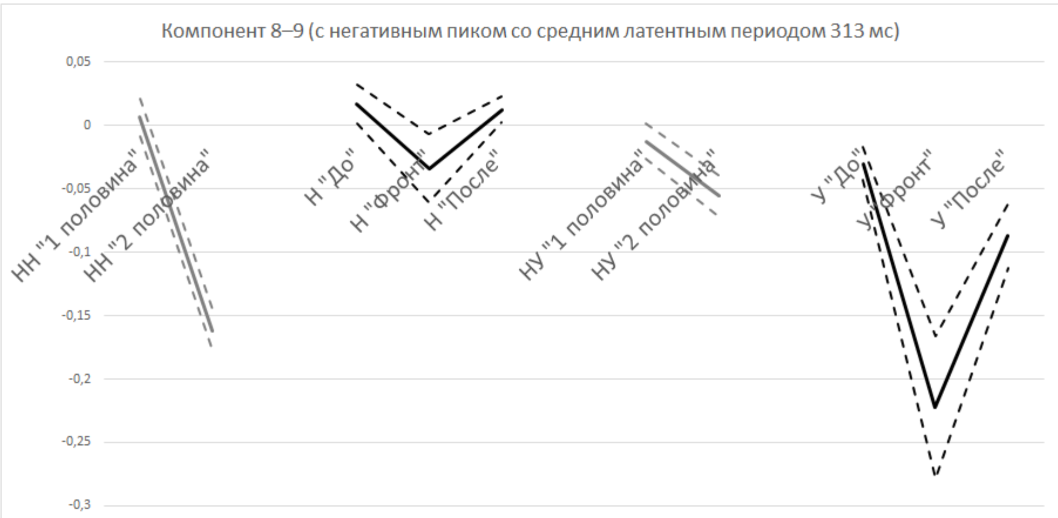
It was shown that the group of those who had not acquired the skill was characterized by a direct relationship between the amplitude of component 6-7 and performance in the second half of the experiment, and a similar direct relationship between the amplitude of component 7-8 and performance in the first half of the experiment. The group of those who had not acquired the skill exhibited the most pronounced covariances, while the group of those who improved the skill exhibited minimal covariances. The group of those who had acquired the skill exhibited no relationship between the amplitudes of these components and performance, suggesting that these components are expressed regardless of performance, and the presence of relationships is a marker of a systemic organization that is not conducive to learning.

Figure 8

Dynamics of covariances between the amplitudes of the "0" group components and performance



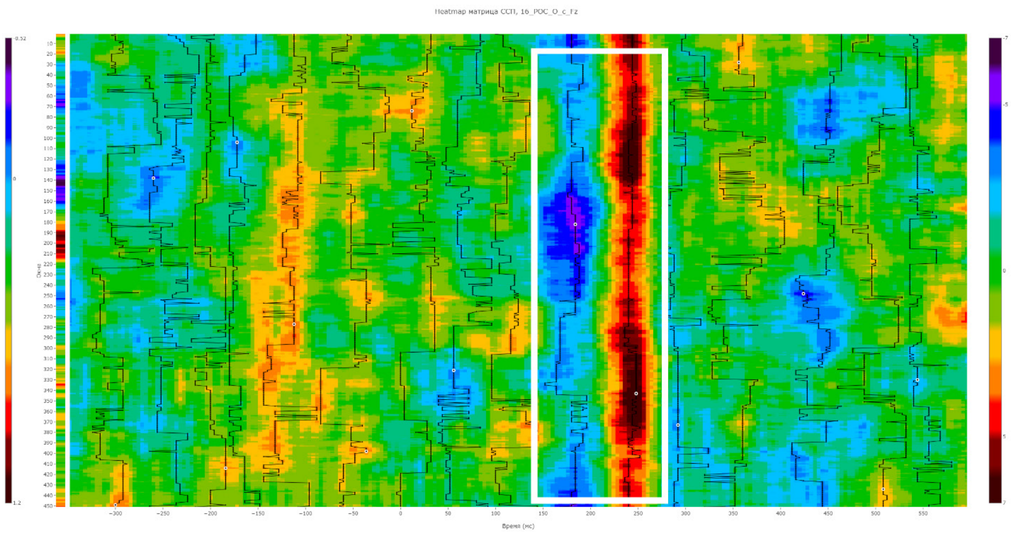




***Note**: Data for individual study participants from 4 groups are shown (NA – those who had **not** acquired the skill; A – those who had acquired the skill; NI – those who had **not** improved the skill; I – those who had improved the skill). The solid line represents the mean covariance value within an epoch, and the dotted line represents the standard error of the mean. Values on the ordinate are given in µV.*

Figure 9

Heat map illustrating the severity of components 6–7 and 7–8 (indicated in a white frame)



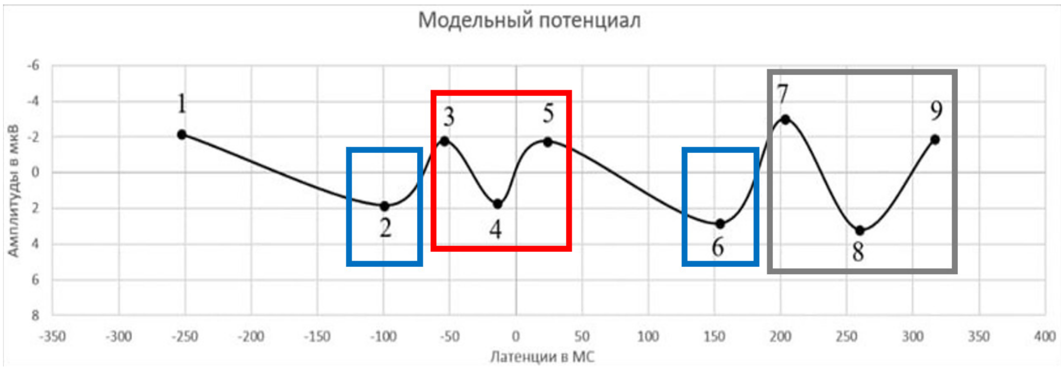
Note*: The abscissa represents time (0 is the start time of presentation of the assessed signal) and the ordinate, from top to bottom, represents the averaging window number from 1 to 451. Negative oscillations are marked in blue, and positive oscillations are marked in red. High color intensity indicates high component amplitude.*

Negative component 8–9 in the group of those who had acquired the skill is also characterized by a lack of correlation between its amplitude and performance; however, in the groups of those who had not acquired and had not improved the skill, a phenomenon mirroring that of the previous two components is observed. In the second half of the experiment, the relationships become inverse. That is, with localized performance increases, this component begins to decline. In the group of those who had acquired the skill, the severity of this component is independent of performance and remains evident throughout the experiment. When comparing the groups, the following can be observed: In the First Half epoch the group of those who had not acquired the skill has higher covariances compared to the group of those who had acquired the skill. However, in the Second Half epoch the group of those who had not acquired the skill has less pronounced covariances compared to the group of those who had acquired the skill. Therefore, we can observe an inverse relationship in the covariance values between the groups of those who had not acquired and those who acquired the skill. A similar phenomenon is observed when comparing the groups of those who had not acquired and had not improved the skill with those who had improved the skill. The group of those who had improved the skill exhibits higher covariances than the aforementioned groups in the Post Improvement epoch.

It was thus demonstrated that the characteristics of the components identified at different intervals of time are associated with the learning process differently. Figure 10 shows a summary of the results.

Figure 10

Model potential with component labels



Note: *Components in the "+" group are highlighted in blue, components in the "-" group are highlighted in red, and components in the "0" group are highlighted in gray.*

Discussion

It was shown that the relationships between performance and the amplitude characteristics of the identified components varied across the different components. Given that ERP components can reflect the degree of actualization of experience systems (the number of simultaneously actualized experience systems) associated with different behaviors (Gavrilov, 1987), the differences can be interpreted as follows: The behaviors performed in response to interactions with the task differed among study participants from different groups. Since the components are characterized by different relationships between their amplitude and performance, we can conclude that the actualization of experience systems at different points in time can either "facilitate" the learning/improvement process or, conversely, "hinder" it.

Component 1-2 (with a positive peak with an average latency of -99 ms) was shown to belong to the "+" component group (reflecting the occurrence of systemic processes that facilitate learning effectiveness). According to the literature, a negative CNV wave might be expected to appear before the onset of the assessed signal, which is also correlated with time estimation (Macar & Vidal, 2004; Kononowicz & Van Rijn, 2011). However, in our study, a positive peak was observed. From the perspective of the systemic-evolutionary approach, this component can be interpreted as the actualization of experience systems that enable the behavior of observing the onset of the presented signal. This suggests that the actualization of experience systems before the onset of the assessed signal is a more productive way of implementing the behavioral act and that the individual is more likely to undergo learning/improvement processes.

In those who had not acquired and had not improved the skill this component is reduced as performance increased. However, the following three low-amplitude components with average latencies of -55 ms, -15 ms, and 22 ms were more pronounced. These trends apparently indicate that the activation of experience systems and the implementation of corresponding behavior during the initial presentation of the assessed signal hinders performance improvement.

Component 5-6 (with a positive peak and an average latency of 154 ms) is characterized by the fact that, when analyzed, the establishment of a direct relationship can be detected after the non-random decision point has been passed. We can assume that, after the acquisition of a new skill, systems are formed that are activated at this point in time during the presentation of the assessed signal. Comparing this component with those described in the literature, based on its latency, it can be considered either a late P100 (Odom et al., 2004) or an early P300 (Polich, 2007). Assuming that the study participant needed to track the onset of signal presentation to assess its duration, the data can be interpreted, in terms of the existing literature, both as activity reorganizations associated with changes in the physical parameters of the environment (Odom et al., 2004) and as a "cognitive" process of initiating the assessment of signal duration (Polich, 2007).

If this component is considered an early positive component associated with changes in the physical parameters of the environment (Odom et al., 2004), it can be argued that a larger number of systems associated with changes in the physical parameters of the environment can be a predictor of learning.

The next two components — negative (with an average latency of 203 ms) and positive (with an average latency of 259 ms) — were the most pronounced. However, no correlations were found in the group of those who had acquired the skill. The direct relationships that are established in the groups of those who had not acquired and had not improved the skill apparently indicate that the presence of variability in this component does not contribute to effective learning, in contrast to its stable manifestation in the group of those who had acquired the skill.

Interpreting these components, we can say that a change in the stage (substage) of the behavioral act is currently occurring (Maksimova, Aleksandrov, 1987). Several hypotheses can be put forward that reveal the substantive aspect of this change in the systems of the behavioral act: This change in the complex of systems may be associated with the maximum duration of one stage (substage) of the behavioral act (Bezdeneshnykh, 1988), or it may mark a subjective "midpoint" in the duration of signal presentation, which allows for a more accurate assessment of the overall signal duration (Yudakov et al., 2023).

Component 8–9 (with a negative peak with an average latency of 313 ms) indicates that, by the second half of the experiment, higher covariance values are observed in the groups of those who had acquired and had improved the skill compared to the groups of those who had not acquired and had not improved the skill. Interpreting the negative wave as an expectation of a change in the relationship with the environment (Kononowicz & Van Rijn, 2011), we can it can assert that in the groups of those who had acquired and had improved the skill, improved performance is associated with a more pronounced expectation of the end of the signal and a more precise assessment of the time interval.

The literature presents conflicting data regarding how the amplitudes of the identified components change during learning. Some studies claim an increase in the components — primarily the negative wave (Poon, 1974; Stuss & Picton, 1978), a decrease in the amplitudes of various components (Peters et al., 1977), a sequential increase in P300 amplitude followed by a decrease (McAdam, 1966; Macar & Vitton, 2004), and a sequential decrease in amplitude followed by an increase (Kecei et al., 2006). We have shown that during the learning process, amplitudes change in accordance with the identification of stages (substages) of the behavioral act. Based on this, we can assume that the different results obtained regarding the relationships between the amplitudes of ERP components and performance are explained by the fact that the authors in the aforementioned studies do not distinguish between the processes of learning and skill improvement. They also fail to take into account the complexity and specificity of the tasks.

Conclusion

Summarizing the analysis of the described components, we can conclude that the identified components, their latent periods and amplitudes depend significantly on the specificity of the proposed task. Based on an analysis of the literature and a comparison of its results with our data, we can conclude that universal patterns of increase/decrease in amplitude are absent and can only be observed when using standardized methods (e.g., a simple choice task). Amplitudes increase or decrease during the learning process depending on the stage (substage) of the behavioral act associated with the functional systems being activated at a given moment in time, manifesting as negative or positive EEG oscillations.

We have shown that positive components with average latencies of -99 ms and 154 ms belong to the "+" component group, reflecting the systemic processes that facilitate learning effectiveness. Negative and positive oscillations with average latencies of -55 ms, -15 ms, and 22 ms belong to the "-" component group, reflecting the systemic processes that do not facilitate learning effectiveness. Oscillations with latent periods of 203 ms, 259 ms, and 313 ms belong to the "0" component group, the intensity of which is not related to learning, which can be interpreted as the necessity of their manifestation regardless of the performance dynamics.

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Konstantin Sergeevich Yudakov carried out experiments and performed data preprocessing.

Vladimir Viktorovich Gavrilov analyzed data and interpreted the results.

Viktor Vladimirovich Znakov interpreted the results.

Vladimir Viktorovich Apanovich developed the research program and contributed to the study design.

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Conflict of Interest Information

The authors have no conflicts of interest to declare.