Relations of Perceptive and Motor Components in the Bimodal Choice Reaction

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Abstract. The reaction time (RT), motor reaction time (MT), sensor event related potentials (ERPs) and lateral readiness potentials (LRPs) have been studied at the equiprobable choice reaction (CR), which was connected with a series of sparks (response with right hand) and clicks (response with left hand) with the 4 s interstimulus interval (ISI) (deviation ±10%).The relation character of perceptive and motor stages at slow (SS) and fast (FS) strategies (250<RT<650 ms and 100<RT<250 ms respectively) has been assessed.

The N2 was mostly expressed at the SS to an auditory stimulus, the eNd was mostly expressed in response to visual signals, and the S-LRP and LRP-R were registered sequentially. The MMN and eNd dominated at the FS to an auditory stimulus, while the C1 and MMN in response to visual signals. The P3 was well expressed in both cases, and the S-LRP and LRP-R occurred simultaneously. The main mechanism of the sensorimotor integration (SMI) at the SS was a single dominant left-hemisphere center, which was formed in the end of the ISI at the stage of anticipation and provided the stages of differentiation (sensor decision) and hand choice in order to perform motor reaction (motor decision) for both visual and auditory stimuli. Two independent centers, one in the left hemisphere, which sustained auditory SMI, and the other in the right hemisphere, which helped form visual SMI, were formed at the FS. Then, the premotor and motor processes became activated in the contralateral hemispheres at both the FS and SS.

KEY WORDS: Choice reaction, visual and auditory RTs, ERP, LRP, relations between the perceptive and motor processes

1 INTRODUCTION

Processes of identification, differentiation and recognition of different stimuli, the results of which initiate the mechanisms of motor decision that determines the behavioral reactions, are important elements of perception. The reaction of differentiation is often used in order to shorten the period of formation of alternative motor responses. This reaction shortens the period of the perceptive processes via sharply decrease in the number of properties analyzed in the differentiated stimuli. This is especially typical for the stimuli of different modality. In particular, these reactions include the bimodal experimental paradigm of the choice reaction (CR), which is connected with alternation of visual and auditory signals.

Two main mechanisms, which provide the realization of the CR may be marked out: the perceptual stages (preprocessing, feature extraction, and identification) and response-related stages (response selection, motor programming, and motor adjustment) [1]. These mechanisms interact with each other and their activities are overlapped in time.

Processing stage, which determines the preparation moment to the following reaction to a current stimulus, is the CNV (E-wave) that mirrors the independent preparation of all motor reactions possible in a certain experimental situation [2, 3], the anticipation processes [4] and making a decision [5].

Presentation of a stimulus activates the feature extraction and identification stages, which under the CR conditions may be divided up to four sequential phases: registration, choice of the sensor channel, identification and categorization) [6, 7]. It is suggested that the registration stage, which is connected with the primary sensor assessment of the stimulus properties, appears in activation of the P1 and N1 for both auditory and visual stimulation. The selection stage is connected with the choice for the following analysis of the relevant sensor channel and is characterized by differential negativity (Nd), which is registered for both auditory[8] and visual stimuli [9]. The identification stage mirrors the final identification of the type of the stimulus and connected with the development of the N2[8, 10]. The categorization stage is aimed at the assessing the significance of a stimulus in a certain task and mirrors the activation of the updating processes for the changing (P3a) and repeated (P3b) stimuli [11, 2].

In spite of the well-composed theory, that explains the sequence of perceptive processes, the question is on which stage the mechanisms of differentiation of two sequential stimuli of different modality and initiation of motor components are realized?

There are several potential mechanisms to differentiate auditory and visual stimuli. Visual stimuli are characterized by the occurrence of the early C1 component, which mirrors the earliest income of visual information into the brain cortex [12-17]. This allows differentiating a visual stimulus from an auditory one at early stages of the analysis. The P1 and the anterior frontier of the N1 characterize mainly the function of the detector neurons, which provide differentiation of individual features of visual and auditory stimuli. The MMN shows the level of differentiation of the preceding stimulus from the current one in a sequence at the preattentive level, thus, allowing involuntarily differentiation of visual stimuli from auditory ones [18]. This is most clearly expressed in the odd ball reaction. The auditory MMN is located bilaterally in the supratemporal auditory cortex with 100 ms latent period [19-21, 8]. Visual MMN is registered in the right parietooccipital area with a spike at 150 – 400 ms after the beginning of stimulation [22, 23]. Early Nd for both auditory (frontal cortex areas, 80 – 250 ms) and visual (parietal cortex areas, 150 – 225 ms) stimuli, which were represented centrally, mirror the central channel choice, providing arbitrary differentiation of modality of the stimuli [24, 9]. The N2 is connected with identification processes, representing the stage of comparison of the current information with the standards of the stimuli used. Together with the similarity assessment processes, it includes the process of differentiation [25]. The categorization stage (P3a and P3b), at which the level of difference between the expected and fulfilled SMIs is particularly assessed, may also be referred to the process of differentiation [11].

Therefore, the differentiation process, which is considered as an element of a perceptive decision making (visual or auditory stimulus), may initiate the motor decision making at the stage of the development of one of the aforesaid mechanisms. It may be suggested that the later mechanism is realized, the fuller set of differences will be used to make a perceptive decision. Apparently, making a perceptive decision at early stages leads to downregulation of the later mechanisms of differentiation and vice versa.

The response selection stage may be activated at one of the stages of the perceptive analysis, which provides reliable differentiating of the alternative stimuli, depending on the reaction strategy. Then, the motor programming stage starts developing that may be explained in two ways [1, 26]. According to the hierarchical editor (HED) model, there are two sequential processes, which provide preparation to the motor reaction chosen [27]. The first is the edit pass (ED) process, which is characterized by the extraction of hierarchically organized information, which is connected with the formation of the required motor components and decomposing them into the elementary units, out of the long-term memory. Then, the execution pass (EX) process is initiated to form the sequence of elementary operations required for realization of the motor response. The two-process model includes the internal (INT) process, which is aimed at the assessing of inner features of motor elements, and the sequence (SEQ) process, which is connected with the formation of the sequence of motor elements [28]. In contrast with the first approach, these two processes are realized in parallel. It is suggested that the motor adjustment stage is connected with premotor processes [29]. The most important behavioral parameters are the RT, which defines the complexity of the CR, and MT, which is connected with realization of a set of sequential elementary motor elements [1, 26].

Processes of the motor decision making, as well as preparation and realization of the SMI, are characterized by the readiness potential (RP) and motor ERP, which are detailed at the LRP-level in the central leads (C3 and C4). This allows identifying the moments of time, which are connected with the end of the perceptive analysis and motor decision making [30, 1, 26]. The LRP is generated in the medial part of the M1 and shows the asymmetry of the ERP, which is connected with motor reaction performed with the contralateral hand [1]. The sensor LRP (S-LRP) starts after the end of the motor selection and in the beginning of the motor program formation. The motor LRP (LRP-R) mirrors the premotor and motor components of motor reaction [1, 26]. Configuration and amplitude parameters of LRP are also used to assess the expression of motor selection and formation of motor reaction.

Study of the mechanisms of organization of the CR motor components is connected with the analysis of the ratios between the RT, MT, S-LRP and LRP-R, which, in particular, mirror the level of interhemispheric asymmetry [30, 1, 2, 26]. This phenomenon may be explained either by a series of sensor or motor effects.

Domination may occur not only in result of sensor asymmetry (especially in case of use of lateralized stimuli), but also in result of switch of attention onto the symmetric stimuli [31]. In the first case, these lateral differences at the level of central leads are connected with the P1 and N1 asymmetry, while in the second case, they are due to the later components, such as the N2, which is believed to be connected with the occurrence of the N2pc in response to a contralateral stimulus.

Motor effects are believed to be connected with interactions between the traces of the preceding and current lateralized motor reactions. The repeat of the reaction with either right of left hand leads to the accumulation of excitation in the corresponding motor center [30, 32, 33]. In this case the center in the contralateral response hand becomes dominant,

A significant role in these cases belongs to the effect of lateral compatibility of a sensor stimulus and motor reaction [30, 31, 1, 34, 2, 26]. Absence of the lateralized stimuli in the testing procedure, as well as the connection of the response hand and the dominating sensory system within the framework of visual SMI, may be considered as the evidence of the formation of a dominant center in the left hemisphere and, respectively, in the right hemisphere in case of the auditory SMI, which is connected with the subdominant left hand.

To decrease the effect of refractoriness and intermodal interactions, as well as for the total realization of all stages of the sensorimotor integration at the stimuli alternation, a relatively large ISI (4 s) was used.

Although individual stages of the CR organization have been described in the modern literature, the character of their relations and principles of interaction, which depend on the reaction strategy, remain poorly studied.

Therefore, there is a wide spectrum of behavioral and electrophysiological parameters in order to study the interactions between different stages of the CR. The main element of these interactions is the level of temporal overlapping of these stages with respect to the independent perceptual and response-related stages. As the sequence of perceptual stages is finished by the stage of categorization, two strategies, in which the RTs were registered before (fast) and after (slow) the P300 development (FS and SS, respectively), were chosen in order to compare the character of interactions between different stages of the CR.

Therefore, the goal of our work was to study neurophysiological mechanisms of interactions between the perceptive and motor stages of the CR organization, depending on the reaction strategy.

2. METHOD

2.1 Participants

The study involved 24 students and researchers (16 male individuals) of Southern Federal University with the average age of 22.4 years. All participants were right-handed people with normal vision and hearing.

2.2 Stimulation

During the experiment a participant was settled in a comfortable chair in a well-lighted room and performed the testing procedure. Sparks formed by a 5 cm diameter matrix of red light-emitting diodes with 9 cd luminous intensity and 1 ms duration were used as visual stimuli. Distance from the stimulation source and the eye surface was 70 cm. Auditory stimulation was performed by clicks with 1 ms duration and 60 dB intensity, which were represented simultaneously with two loudspeakers places within 5 cm from each ear respectively.

2.3 Procedure

Each participant underwent a long-term testing procedure (2 h each) under the choice reaction conditions aimed at differentiating of visual and auditory stimuli, which were represented with equal probability (0.5). Gaze was fixed upon the spark. In case of representation of a visual stimulus, the participant was supposed to press the right button of the mouse manipulator with his right hand thumb. Conversely, when an auditory stimulus was represented, the participant was supposed to press the left button of the mouse manipulator with his left hand thumb. These activities were considered as realization of the sensorimotor reactions. Each testing procedure included 1600 stimuli with the average ISI of 4 s (the mean value deviation was ±10%).

2.4 EEG

The EEG was registered with 21 standard leads (the 10 – 20 system), 4 ms digitization step and 0.5 – 70 Hz transmission frequency with respect of the combined ear electrodes. The indifferent electrode was placed upon the forehead. Artefacts were eliminated with the EEGLAB software as described in [35].

2.5 Data reduction and statistical analysis

To analyze the experimental data, two groups of reactions were marked out as the correct SS (250<RT<650 ms) and correct FS (100<RT<250 ms) responses. The incorrect SS, FS and late responses (RT>650 мс) were excluded from the analysis because of their small number and/or high variability.

Digitalized EEG, RT and MT were exported into the MATLAB program, in which total sensory ERPs (100 – 500 ms after stimulation) were obtained. The S-LRPs for the visual stimulation were calculated by subtraction of the sensory ERPs in the C3 lead out of the ERPs in the C4 lead. The converse procedure was carried out in order to obtain the S-LRP for the auditory stimulation. Time parameters of the LRP were assessed as described in [34]. For more detailed characteristics of the SMI we used the MT that was assessed as the difference between the moments of pressing and release of the buttons.

Confidence of differences between the RT and MT, as well as between the ERP and LRP fragments was estimated by the multifactor variation analysis (ANOVA).

Isopotential maps were composed by the method of spline interpolationof values under the electrodes, which were topographically positioned on the 2-D image (top view), using the algorithm provided in the EEGLAB program [35]. The 10 ms step was used to assess the dynamics of the isopotential maps in the period of ERP development in order to reveal the formation periods and localization of the maximal expression foci (MEF) of each component.

The summarized ERP and LRP schemes for assessment of the ratios between their different components, were composed by connecting of the maximums of the sequential components with straight lines [34]. Auditory LRPs were inverted.

3 RESULTS

Under the conditions of the equiprobable bimodal CR, the number of the correct and incorrect SS, as well as the correct FS depended evenly on the stimulus modality. Portion of the reactions to the visual stimuli in the aforesaid groups was 75%, 3% and 16% respectively, whereas for the auditory stimuli it was 77%, 3% and 14% respectively.

3.1 Behavioral data

The analysis of behavioral parameters revealed high accuracy of the performed experiments (the number of errors varied from 5.5% to 5.6%) and shorter RTs: F(1,36601) = 572.01, p=0.000 at visual stimulation (Table 1). In case of incorrect reactions, in which hands were interchanged during pressing the buttons of the mouse manipulator, the RT parameters remained unchanged.

Table 1. Reaction time (RT) and Standard error of the mean (SEM) to visual (V) and audial (A) stimuli in the slow (SS) and fast (FS) strategy

Strategy	100<RT<650 ms (SS+FS)		250<RT<650 ms (SS)		100<RT<250 ms (FS)	
Modals Parameters	V	A	V	A	V	A
Right trials						
N	18254	19087	13784	13858	3059	2826
RT±SEM	353±1,0	390±1,2	352±1,1	389±1,3	226±1,5	216±1,5
MT±SEM	185±0,7	203±0,8	230±0,8	210±1,0	163±1,7	180±2,2
Error trials						
N (%)	1091 (5,6)	1113 (5,5)	859 (5,9)	876 (5,9)	232 (7,0)	237 (7,7)
RT±SEM	353±4,8	391±5,2	346±5,8	378±5,6	200±9,9	198±1,2
MT±SEM	191±7,2	192±10,8	188±11,9	195±18,8	192±11,7	191±15,2

At the slow strategy of the reaction to a visual stimulus, the RT was shorter (340 ms) (($F(1,36601)=572.01$, $p<0.001$)) than that in the reaction to an auditory stimulus (380 ms). In case of the fast strategy, shorter RTs were observed in response to an auditory stimulus (217 ms) as compared with the visual stimuli (223 ms) ($F(1,36601)=572.01$, $p<0.001$).

The MT to the visual stimuli at the slow strategy was longer ($F(1,36601)=572.01$, $p<0.001$) than to the auditory stimuli. In case of the fast strategy, the visual MTs were shorter as compared with the auditory ones.

3.2 ERPs

The analysis of sensory ERPs showed that their configuration depended on the electrode localization, stimulus modality and the reaction strategy (Fig. 1). The ERP obtained in response to the auditory stimuli was characterized by a set of the classical components, such as the CNV, P1, N1, P2, N2, P3a and P3b. Visual stimuli induced early occurrence of the C1 component. Different reaction strategies were characterized by the presence of additional differential negativities (Nd): the Nd1 developed within the "N1 spike – the descending part of the N1" interval (the increase in the N1 amplitude); the Nd2 developed within the "descending part of the N1 – ascending part of the N2" (the inhibition of the P2).

If we take for the standard the correct responses under the SS conditions, which, at the auditory stimulation, were characterized by well-expressed the CNV, N1, P2 and N2 and poorly expressed the P3b and P3a, whereas at the FS conditions the increase of the CNV and Nd1, the occurrence of the Nd1, preservation of the Nd2, significant increase of the P3b and P3a took place.

Standard of the correct answers to the visual stimuli under the SS conditions was characterized by well-expressed CNVs, C1, P1, N1 and Nd2 and poorly expressed the N2, P3b and P3a. The FS was characterized by increase of the CNV, C1, N1 and Nd1, appearance of the P2, disappearance of the Nd2 and significant increase of the P3b and P3a.

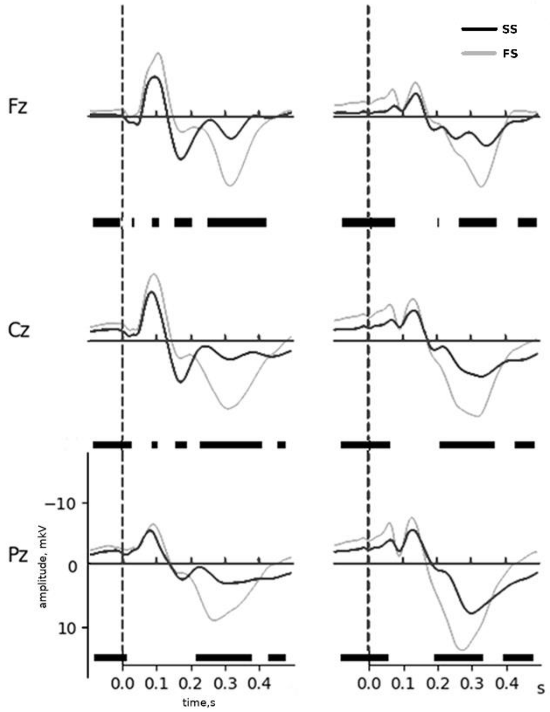

Fig 1. The dependence of visual and audible ERPs at different reaction types (SS, FS). Bold segments - intervals of the differences ($p<0,01$).

The analysis of the isopotential maps allowed us to assess the dynamics and localization of the ERP components that depended on the reaction strategy. In case of the SS, the auditory ERPs were characterized by the prestimulatory CNV, the negative focus of which was located in the parietal associative cortex in the Pz lead, which is shown on the Fig. 2 within the 0 – 0.06 s interval. Simultaneously, in the 0.03 – 0.06 s interval, a poorly expressed positive spike of the P1 component was formed. During the formation of the ascending part of the N1 (0.07 – 0.14 s) the spike CNV was shifted in the central-frontal direction with the following shift into the corresponding temporal leads with domination of the left hemisphere.

The symmetrical ascending and descending parts of the P2 was developed within the 0.14 – 0.24 s interval and demonstrated the spike in the Fz lead. The formation of the N2 with the MEF in the Fpz lead, which dominated in the right hemisphere, was observed within the 0.25 – 0.29 s interval. The P3b with the spike in the Pz appeared within the 0.25 – 0.51 s interval and further (0.51 – 0.49 s) was split into two symmetric parietotemporal spikes, which dominated in the right hemisphere. Simultaneously, a negative symmetric component with the spike in the Oz occurred. At the same time, the P3a component (0.31 – 0.35 s) with the spike, dominating in the left hemisphere (the F3 lead), as well as the symmetric N400 (0.36 – 0.59 s) with the spike in the Fpz lead, were developed.

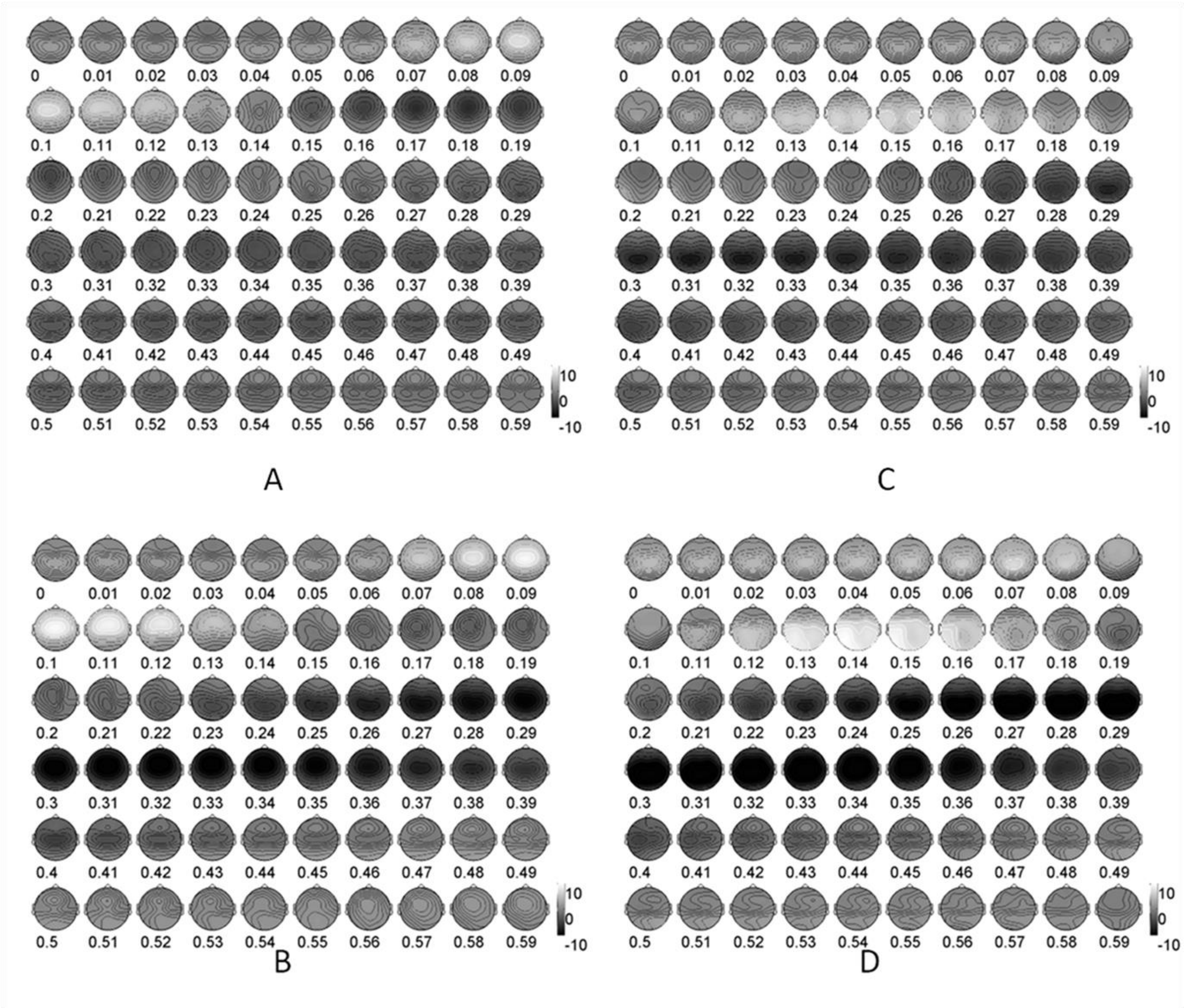

Fig. 2 Isopotential maps in dynamics of audible (A, B) and visual (C, D) ERPs (10 ms step) at the SS (A, C) and FS (B, D)

In case of the FS, the increase in the CNV amplitude was observed in the same location alongside with simultaneous appearance of the asymmetry (domination of the left hemisphere) within the 0.03 – 0.06 s interval that was preserved at the ascending part of the N1 (0.07 – 0.10 s). Domination of the right hemisphere occurred in the prolonged descending part of the N1 (0.11 – 0.16 s) due to the development of the corresponding Nd1, leading to the increase in the N1 amplitude, the spike of which dominated in the left hemisphere (0.16 – 0.20 s). Prolongation of the descending part of the N1 and inhibition of the P2 corresponded to the increase of the Nd2. Further (0.19 – 0.28 s), the N2 with the spike, dominating in the right hemisphere, appeared in the Fp leads. Then a group of symmetric high amplitude components of the P3 (0.21 – 0.49 s), which began with the P3b (0.21 – 0.27 s) with the spike in the Pz, was formed. Then, the P3a (0.28 – 0.37 s) with the spike in the Fz was added and increased, and, in the 0.38 – 0.47

s interval shifted into the Cz. Simultaneously, the decrease of the P3-components prolonged the latency of the N400 and the late negative wave with the spikes in the Fpz and Oz respectively, which further merged into the N600 component with the spike in the Fz (0.56 – 0.59 s).

In case of the SS, the visual ERP was characterized by the prestimulatory CNV, the negative spike of which was located in the temporal associative cortex in the Pz lead, which is shown on the Fig. 2 in the 0 – 0.05 s interval. Then, the symmetric C1 appeared in the Pz within the 0.06 – 0.08 s interval. Simultaneously, a weakly defined positive component of the P1 appeared in the 0.07 – 0.1 s interval, dominating in the right hemisphere (the O2 lead). The formation of the rise-up portion of the N1 (0.09 – 012 s) was followed by the spike CNV shift in the central direction. The latter was further split in the descending part of the N1 (0.13 – 0.24 s) into the symmetric spikes, which were then shifted into the corresponding parieto-temporal-occipital leads with domination of the left hemisphere. The P2 developed in the 0.18 – 0.25 s interval and was characterized by the spike in the Fz lead. The low amplitude of the P2 was due to the development of the Nd2. In the interval of 0.25 – 0.39 s the P3b with the MEF in the Pz was formed. Further (0.37 – 0.49 s), the P3b was split into two symmetric parietotemporal spikes with domination of the left hemisphere. Simultaneously with the P3b a negative symmetric component with the MEF in the Fpz appeared in the 0.40 0 0.59 s.

In the 0.00 – 0.18 s interval, the FS at the visual stimulation was characterized by the same ERP components with the same localization as in case of the SS, but with higher amplitude. At this time, the Nd1 developed on the N1 spike, while on its descending part (0.13 – 0.18 s) the Nd2 disappeared, resulting in the enhancement in the P2. Then, in the 0.19 – 0.30 s interval, the spike was formed in the Pz P3b, which transformed into the P2a (0.30 – 0.42 s) with the spike in the Fz and split into the two spikes with domination in the left hemisphere. Then the N400 with the spike Fpz appeared (0.41 – 0.49 s), which was followed by the N600 component with the spike in the Oz (0.41 – 0.49 s).

3.3 Motor ERPs

The S-LRP and LRP-R analysis revealed a considerable dependence of motor ERPs on lateralization of the hand, which realizes the motor reaction, as well as on the reaction strategy and coinciding of temporal parameters of their components with a series of components of sensor ERPs in the Cz lead (Fig. 3 A).

The premotor reaction to the visual stimuli in the left hemisphere (when the mouse manipulator button was pressed with the right hand) was the most obvious. This reaction was connected with the formation of the negative-positive S-LRP (Fig. 3B). The first negative wave was registered within the 0.02 – 0.30 s interval, beginning from the moment of stimulus representation, and its spike coincided with the development of visual P2. The following positive wave was characterized by 0.30 s latency, 0.40 s spike latency and coincided with the development of the descending part of the P3.

The S-LRP, which appeared in response to the auditory stimuli (pressing of the button with the left hand) was associated with the development of a positive-negative complex. The positivity was formed in the left hemisphere before the moment of representation of the auditory stimulus, and its spike latency coincided with that of the auditory N1. The end of the positive wave coincided with the spike latency of the visual negative S-LRP. The negative spike, which appeared in the right hemisphere, coincided with the development of the rise-up portion of the auditory P3.

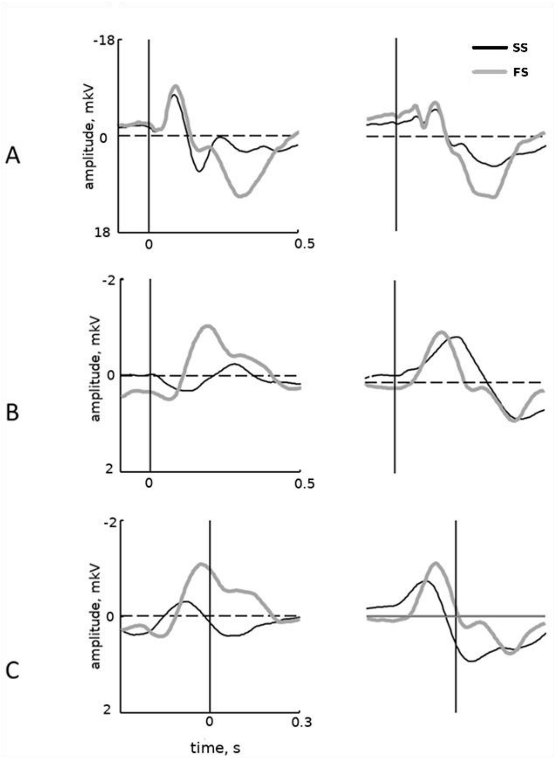

Fig. 3 Comparative analysis of visual and audible ERPs in the leads Cz (A), S-LRP (B) and LRP-R(C) under the SS and the FS conditions.

The comparative analysis of the visual and auditory LRP-Rs showed that in both cases the motor reaction was overcome by the development of negative wave, which was expressed stronger and demonstrated shorter spike latent period in response to visual stimuli. However, this negative fluctuation was preceded by a positive component, which was developed in response to the auditory stimulus, whereas negative component was developed in response to visual stimulation.

Study of the error reactions revealed the decrease in the amplitude of the main ERP components in the Cz. In this case, the inversion of the S-LRP, which did not affect its configuration, was observed alongside with the decrease in the latent period, spike latency and increase in the amplitude of the negative component of the S-LRP.

In case of the FS, the increase in the amplitude and decrease in the latent period of the S-LRP and LRP-R were observed. Shorter intervals from the LRP-R spike to the moment of the beginning of the movement were also registered (Fig. 3 C).

4 DISCUSSION

In the present study we showed that there are two main reaction strategies of the bimodal equiprobable CR: the FS and SS. The SS was typical for frequent reactions (about 75%), which occur after the development of the P3 and are adequate for the testing procedure. The FS reactions occurred rarely (about 15% of all reactions), were associated with short RTs and appeared spontaneously, before the development of the P3. It maybe suggested that additional elements of the odd-ball reaction are realized within the CR, suggesting that the expected event was the SMI at the SS, while the unexpected one occurred at the FS.

The RT of the correct and incorrect answers at the SS was connected with the modality of the stimulus and did not depend on the hand change in the SMI. It was be hypothesized that the perceptive analysis, which was performed much faster for the visual system and required considerable volitional attention, dominated in the CR organization in case of the SS. In case of incorrect answers, the MT decreased significantly at both SMIs and depended of the hand change. This is apparently due to the higher level of automatization of motor responses.

In accordance with the odd-ball logics, the RTs should be longer in case of the FS, which is connected with rare events, as well as with competition between the volitional processes and the reference attention components, than in case of the SS. It appears, that the alternative results obtained may be due to the domination of motor processes, in case of the FS, that determined a fast response, while domination of the auditory system was connected with non-volitional attention components.

In case of the FS the MT was shorter than in case of the SS. This may be considered as the evidence of even higher level of automatization of motor responses. The left hand (subdominant), which is controlled by the right hemisphere, connected with domination of the non-volitional attention mechanisms, was characterized by slowest responses.

Therefore, the RT and MT depended on the sensory systems (auditory and visual), which determined the signal processing rate with the balance of volitional and non-volitional attention components. This balance is determined by the reaction strategy and/or by the hand used to the response. In case of the SS (expected event) and/or use of the right hand the additional components of volitional attention (left hemisphere) were activated, whereas the FS (unexpected event) and/or use of the left hand led to the activation of additional components of non-volitional attention (right hemisphere).

The total reaction time (RT) that equals to the sum of RT and MT decreased from the correct (about 600 s) answers in case of the SS. The shorttr RT was observed in case of the FS (about 400 ms) that is, apparently, due to the substitution of the sensory domination in the first case with motor domination in the third case. On the other hand, it may be suggested that switch from the SS to the FS is followed by the change of the sequential fulfillment of the perceptive and motor processes for parallel, because of their superposition. This trend was characterized by the proportional dependence of the MT on the RT, apparently, due to the complication of the motor component alongside with the increase in the RT [36].

4.1 Sensory ERPs

The additional components isolated, which were connected with differential negativity (Nd1 – Nd2), are considered to be independent and mirrored a variety of aspects of stimulus differentiation. In this experimental situation, the Nd1 may correspond either to the MMN and/or early differential negativity (eNd) that may be verified by the analysis of sequential passive effects. It may be suggested that the Nd1 is represented by the MMN, because they are characterized by a corresponding spatiotemporal localization and occur in case of rare events only, which correspond to the odd-ball elements of the CR studied [19, 22, 8]. It appears that the MMN occurred in response to the changes in the parameters of the memory trace at the moment of change of the functional condition during the switch from SS to the FS rather than in response to changes of physical parameters of the stimulus. On the other hand, the Nd2 corresponds to the early differential negativity and mirrors the process of the memory channel choice at the CR [6].

The hypothesis of [6] and the data obtained allow us to suggest that differentiation of stimuli in case of the SS at the auditory SMI was performed at the stage of identification (N2), resulting in the absence of expressive MMN and eNd. Differentiation of the auditory stimuli in case of the FS took place at earlier stages, which were connected with intensification of the preattentive processes (MMN) aimed at the differentiating of the sequential stimuli, as well as activation of the volitional attention components at the stage of the sensory channel selection (eNd). This removed the necessity in identification of the stimulus (suppression of the N2).

Apparently, in case of the SS, differentiation of visual stimuli was performed at the stages of the sensory channel selection (eNd). In case of the FS, differentiation of visual stimuli occurred at earlier stages, which were connected with activation of the C1 and MMN components, resulting in the suppression of the eNd and N2.

It has been suggested that at short RTs the stimulus was analyzed partially, whereas at long RTs it was fully analyzed [38, 39]. This may be considered as the evidence of more obviously expressed updating processes (P3a and P3b) in case of the FS. On the other hand, it may be suggested that at short RTs (FS) the P3 is sensitive to both stimulus- and response-related processing [11, 40, 41].

The P3b dominated under the conditions of the SS-type reaction to a visual stimulus owing to the activation of the volitional attention mechanisms. In case of the FS-reaction in response to both visual and auditory stimuli, the P3b increased and was followed by the high amplitude P3a, which mirrored activation of the non-volitional attention components [11].

The observed differences in activation of the perceptive stages of the reactions to both visual and auditory stimuli for both strategies (SS and FS) may be considered as the evidence of domination of one of these SMIs.

4.2 Motor ERPs

It was previously shown that at the short MTs the motor ERP appeared at the stage of button pressing only (on-reaction) that corresponds to the FS. When the RT values increased 250 ms, an additional motor ERP occurred and increased at the moment of button release (off-reaction). This ERP was further transferred into an independent event that attracted a part of attention resources, pointing at the SS. Hence, switch from the FS to the SS leads to prolongation and/or complication of the motor component of the CR.

4.3 Motor LRPs

The Fig. 4 shows the schematic images of the ERP and LRP, which were obtained as described in [34]. These images show that the advantages of the visual motor reaction in comparison with the auditory one, under the SS conditions, were due to the higher amplitude and shorter spike latent periods of the S-LRP, as well as the presence of a preliminarily shortly latent activation of the contralateral left hemisphere. This led to the domination of the left hemisphere in the motor cortex that increased sharply once the information about the visual stimulus reached the cortex (circle 1). It was also connected with the sensory choice making (S-LRP latency) at the stage of its registration (P1 and N1) and was followed by initiation (circle 2) of the premotor and motor components (LRP-R) at the stage of the sensory channel selection (Nd). At this time, a negativity, which possibly corresponds to the readiness potential (RP) (prior the circle).

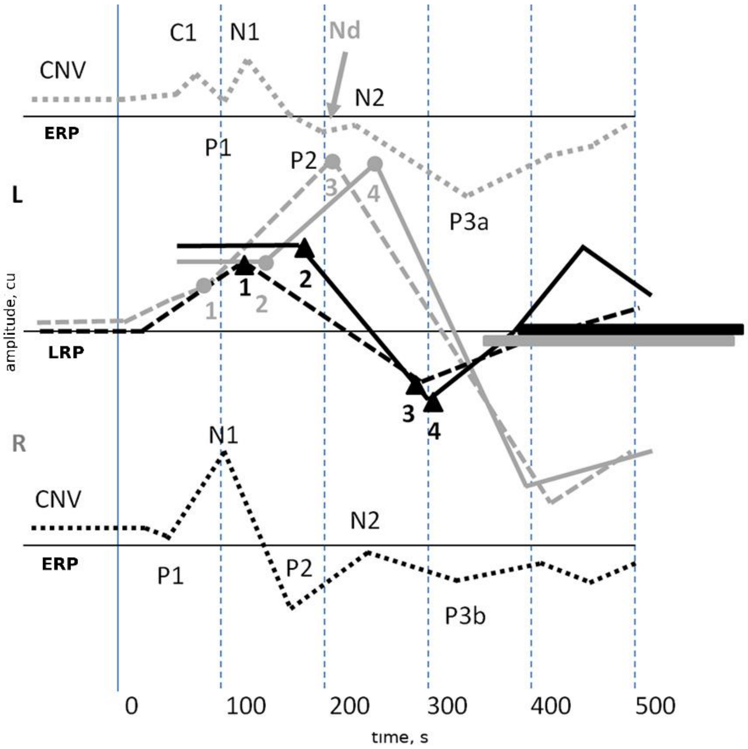

Fig. 4 Comparison of the visual (gray lines) and audible (black lines) ERPs (dotted), S-LRPs (dashed), LRP-R (continuous) schemes and MT (thick lines) under the SS conditions (L – left hemisphere, R – right one). See the text for more detailed explanations.

Reach of the domination maximums of the left hemisphere by the S-LRP parameters (circle 3) and, in 60 ms, by the LRP-R parameters (circle 4) led to the decrease in the activity and formation of the right hemisphere domination phase. However, taking into account that the positive P3 develops at this stage and dominates in the left hemisphere (see the maps), the data obtained may be considered as prevailing of the updating processes in the left hemisphere. Therefore, domination of the left hemisphere was observed at the perceptive and motor stages of visual SMI at the RT period.

Domination of the left hemisphere, ipsilateral to the left hand, was also observed during the auditory stimulation at the stages of sensory decision (by the S-LRP parameters; triangle 1), RP development (prior the triangle 2) and premotor and motor components (by the LRP-R parameters). Then, however, the hemisphere, which provided the realization of the auditory SMI, became dominating by the S-LRP and L-LRP parameters (the triangles 3 and 4 respectively). Change of the dominating hemisphere from ipsi- to contralateral one with respect to the left hand led to later activation of the latter and, thus, longer auditory RTs as compared with visual ones. Afterwards, the domination shifted to the left hemisphere at the P3 stage, possibly showing the prevailing of the updating processes in the right hemisphere. This supports the conclusion about domination of the right hemisphere in the RT period.

Preliminary activation of the left hemisphere for both auditory and visual stimuli is apparently connected with the formation of a single center for sensory and motor decision, as well as initiation of the pre-motoring processing for both SMIs in the dominating left hemisphere, in order to provide a single mechanism for the CR realization at the SS. This integration of the left hemisphere may be due to the domination of the visual system and dextrality of the individuals. It may be formed in result of the "training" (automatization) owing to long repeated attempts. On the other hand, this may be favored by long-term fixation of the volitional attention on the spark in the ISI (according to the subject's reports).

In case of the FS (Fig. 5), both auditory and visual reactions begin from a significant activation of the CNV and the RP in the ipsilateral hemispheres. At the stages of the C1 and P1 development, both the S-LRP and LRP-R appear simultaneously, pointing at the parallel development of the perceptive (circles and triangles 1) and motor processes (circles and triangles 2). Synchronous development of the S-LRP and LRP-R leads to the activation and domination of contralateral hemispheres (circles and triangles 3 and 4).

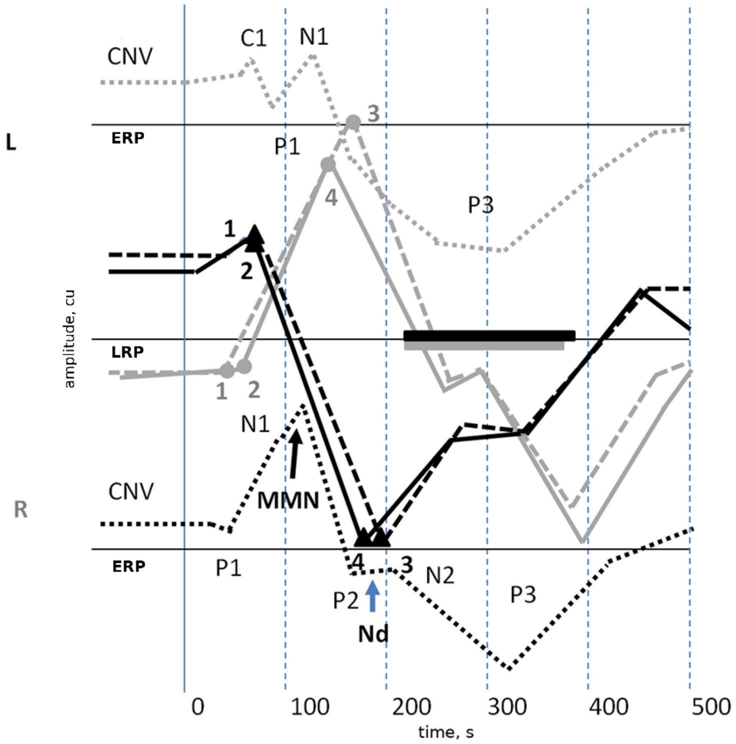

Fig. 5 Comparison of the visual (gray lines) and audible (black lines) ERPs (dotted), S-LRPs (dashed), LRP-R (continuous) schemes and MT (thick lines) under the FS conditions (L – left hemisphere, R – right one). See the text for more detailed explanations.

Therefore, visual and auditory SMIs were organized independently at the FS and were realized by hemispheres contralateral with respect to the hands used. The repeated small oscillation of the S-LRP and LRP-R at the FS may be due to the attempt to repeat the motor reaction, which is possibly formed via the SS strategy type.

Therefore, in case of the FS, the S-LRP and LRP-R were characterized by increased amplitude and shortened temporal parameters that may be considered to be the evidence of stronger activation of the motor structures in comparison with the SS, in case of which the perceptive processes dominate.

Synchronism of the perceptive and motor processes at the FS, as well as their dissociation in case of the SS may evidence that in the first case the mechanism of the SMI realization is closer to the two-process model [28], while, in the second case, it is closer to the HED model [27]. Ratio of the MTduration and motor reaction complexity (number of elementary actions), which are proportional to the RT, but not connected to each other, is believed to be an important element [1, 26].

In result of our study we have shown that the RT and MT are increased during the switch from the FS to the SS strategy. On one hand, this increase is apparently due to the growth of the level of dissociation between the perceptive and motor processes that provides more effective distribution of the attention resources between them and allows fuller realization of the motor reaction, increasing its duration. On the other hand, the increase in the MT is associated with occurrence of the off-component of the button release that increased the complexity of the motor reaction and was connected with weakening of the refractory effect after pressing of the button (on-reaction). Hence, mechanisms responsible for the increase of duration and complexity of the motor reaction, are believed to be of different nature and independent from one another.In case of the FS, complication of the motor component was due to the appearance of an additional LRP oscillation at the stage of its preparation. However, it did not apparently realized at the behavioral level, because of refractoriness and deficiency of the attention resources, and thus, did not affect the MT.

5 CONCLUSION

There are two main strategies of the SMI formation within the framework of the bimodal CR. These strategies are characterized by different probability (the FS is associated with rare events, whereas the SS is associated with often events), additionally complicating the testing procedure because of the odd-ball mechanisms. Each strategy is realized via five sequential-parallel channels of information processing, including anticipation (choice of the reaction strategy), perceptive analysis, which completes the sensory decision making, motor decision making and organization and realization of the motor reaction. Each channel includes several mechanisms. The channels interact with one another and their activities are overlapped in time. Changes in the behavioral parameters are connected with variation of duration of each stage, as well as with the level of their superposition.

The main mechanism of the SMI at the CR (SS) experimental design used is the single dominant left hemisphere center, which is formed in the end of the ISI at the stage of anticipation and provides the stages of differentiation (sensory decision) and hand choice in order to perform the motor reaction (motor decision).

Use of the left hemisphere is due to its domination in the organization of the volitional attention components, significant resources of which are required to realize the perceptive and motor components of both auditory and visual SMI and especially to activate the visual system [42]. The long-term combination of activation of visual system, which is additionally activated in the ISI because of fixation of the glance upon the spark, and the leading right hand, the motor center of which is also located in the left hemisphere, allows it to integrate dominant perceptive components and provides the motor decision.

Sensory and/or motor decisions initiate the mechanisms of preparation and realization of the lateral motor reactions, the formation centers of which are independent and located in the corresponding contralateral hemispheres [43], together with the categorization stage. Both duration and complexity of the motor response are determined by the volitional attention resources, which are upregulated alongside with increase in dissociation of the perceptive and motor processes.

The derangement of the formation of the dominant center in the left hemisphere aimed at the perceptive and motor decision making, which may occur at excessive motivational overexcitation of the hemispheres ipsilateral with respect to the hand used, is associated with realization of the rarely FS. It is connected with disintegration of the single center in the left hemisphere into the right and left hemisphere centers. In this case, the center of the perceptive and motor decision in the left hemisphere supports auditory SMI, while the center in the right hemisphere is responsible for the visual SMI, which initiate pre-motor and motor processes in the hemispheres contralateral with respect to the hand used. The processes develop further similarly to the SS, though they demonstrate two features: 1) full synchronism (simultaneity) of the development of both perceptive and pre-motor processes and 2) appearance of the additional motor component in the LRP.

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