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Frontoparietal Patterns of Delta and Beta EEG Oscillations as Markers of Creativity Strategies

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Abstract—Recently, there has been considerable interest in the mechanism of cooperation between the frontoparietal system and the default system, since their "pre-tuning" at rest and the subsequent functional interaction dynamics is associated with individual variety of strategies for task performance upon creativity testing. To study the EEG correlates of these strategies, regional features of resting state Δ- and β-oscillations were analyzed and compared with the results from preliminary creativity and intelligence testing in 37 university students (18 ± 1.1 years; 27 females and 10 males). The response originality indices in the creativity tests were calculated using databases previously designed by the authors for the "Circles," "Incomplete figures," and "Unusual use of ordinary objects" subtests and an expert assessment of originality of the sentences composed of words belonging to different semantic categories. The intelligence verbal and figurative components were assessed according to the Amthauer intelligence structure subtests. Using cluster analysis of the listed creativity and intelligence indices, two groups of study participants were identified. One of the groups (GR_{CIQ}) was characterized by a combination of higher values of intelligence and originality of responses in the tasks that required the rejection of stereotypical ideas upon limited search time, and the other group (GR_C), characterized by relatively lower intelligence, but high originality of solving the problem upon the creativity testing with a variety of stimuli and without time limits. These two groups differed in regional organization of the Δ- and β_2-rhythm power and in the rhythm correlation patterns. In particular, GR_{CIQ} is characterized by generalized high-frequency β-activity and its correlation with low-frequency biopotentials in the frontal cortex, while GR_C is characterized by cortical mosaic of the β_2-activity with its diffusely distributed correlations with the Δ-rhythm with the exception of the anterior frontal areas. The discovered effects can be considered as a pretuning to the "intelligent" search strategy for an original solution in the conditions of resistance to fixation on a stereotyped idea in GR_{CIQ} or to solutions based on spontaneous search for distant associations in GR_C.

Keywords: creativity, intelligence, EEG, frontoparietal system, default system, Δ- and β-oscillations

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INTRODUCTION

Recent active neurophysiological studies of creativity, are focused on elucidating the patterns of cognitive processes that underlie the mechanisms for finding original solution to a problem, including the role of intelligence and execution control in solving a task or the contribution of insight strategy [1–5]. There is still no consensus in understanding the relationships between creativity and intelligence, apparently due to the fact that these psychometric constructs represent a complex set of mental operations, including attention, memory, imagination, association formation, which are used to varying degrees in solving experimental problems. Recent studies of the interaction between creativity and intelligence, mainly using tomographic methods, indicate their common structural elements in the neural architecture of the brain [5], and psychometric data point to functional similarity of information selection processes [4]. However, it remains unclear whether this similarity is ensured by the generalized or specific neural systems required to perform experimental tasks of verbal or figural nature. For these reasons, the issues whether creativity is a component of intelligence, or on the contrary, is intelligence included in the structure of creativity, or are creativity and intelligence connected through common neural mechanisms of information selection and the use of memory resources, remain relevant.

In addition to the data on wide representation of brain structures in association with both creativity [6–11] and intelligence [12–16], there is evidence that the association of these cognitive constructs relies mainly on the interaction of frontal cortical areas involved in executive functions and the posterior cortical regions or frontoparietal network (FPN) and default mode network (DMN) systems [5, 6, 16]. Moreover, the executive control of attention is considered as a factor that regulates the contribution of fluid intelligence and "mind wandering" to creative thinking, which at its different stages have both positive and negative value [5].

At present, much attention is paid to the mechanisms of FPN and DMN cooperation, since their pretuning at rest and the dynamics of functional interaction is associated with individual variety of task performance strategies in both verbal and figural creativity tests [3, 17]. For example, it was demonstrated that the FPN was a mediator of the association between verbal creativity and activity of the anterior DMN, and between figurative creativity and the DMN posterior part [17]. The increased contribution of the FPN reflects the dominance of executive control in the search for new solutions to the problem, while the DMN contribution reflects spontaneous generation of ideas [6, 7, 18]. According to different authors, creative thinking is accompanied by dynamic reorganization of these systems with regional expansion of functional neural networks, including the left middle temporal gyrus and auditory system for verbal creativity [19] or the temporoparietal and prefrontal areas for figurative creativity [20]. Moreover, in the latter case, the specificity of the involvement of individual areas of the indicated cortical regions was determined by factors formed from different creativity indices. In particular, the factor related to fluency and originality was found to be positively associated with brain volume in structures close to the DMN, and the factor that combined indices of elaboration of the drawing and fixation resistance was associated with the frontotemporal regions.

In the process of data accumulation, the initial idea on the right hemisphere dominance in solving experimental creative tasks [21] was changed, since the involvement of the left dorsolateral prefrontal cortex [22] or the left anterior cingulate cortex [20] was demonstrated, for example, in non-verbal creativity testing. Moreover, lateral changes of functional connectivity measured in the dorsolateral prefrontal cortex associated with nonverbal creativity were found to be dependent on FPN and DMN activity [23]. At the same time, new evidence of the crucial importance of right frontal cortex functions for the success of divergent thinking has appeared, which were obtained on the basis of the analysis of different intelligence components, namely fluid, crystallized (which was tested using verbal tasks), and visual-spatial [5]. Therefore, to understand the formation patterns of different functional neural systems that provide different forms of creativity, and the features of their reorganization depending on the structure of intelligence, further studies are required.

To study the functional importance of the resting brain, not only its tomographic, but also encephalographic characteristics are used [1, 23–25]. Among different EEG frequency ranges, synchronization/desynchronization of α-oscillations is considered more often than others, which is due to their information content in relation to the specificity of inhibition/activation processes in neural networks reflecting both creativity and intelligence (IQ) [1, 26–28]. It was demonstrated that the fluid IQ variability was associated with the updating of working memory, while the creativity predictors were represented not only by this component of the executive system, but also by inhibitory functions [27]. The balance of resting state activity in the frontal and posterior cortex may reflect the individual style of solving problems, including the preference for insightful or analytical strategy [2, 27, 29, 30]. Moreover, not only α, but also low-frequency Δ-, θ-, and high-frequency β-oscillations are considered as indicators of such a balance [18, 24, 31–33]. The Δ-rhythm is of interest for the analysis of creativity, since an increase in its power reflects the suppression of learned dominant behavior and indicates the effectiveness of new learning, while θ- and β-oscillations are considered as encephalographic correlates of information processing due to DMN and FPN functions [31, 34].

Previously, we revealed an increase in the interaction of neural ensembles of the anterior cortex with the posterior parts of the left hemisphere in individuals characterized by relatively high levels of intelligence and creativity compared to those who had lower levels [1]. Later, it was found that frontal Δ- and β-rhythms could serve as predictors of both non-verbal creativity and verbal intelligence [32]. The objective of this study was to elucidate the regional features of the Δ- and β-rhythm patterns, as pre-tuning for the realization of verbal or non-verbal creative activity and its potential connection with the values of the verbal and visual-spatial components of intelligence.

MATERIALS AND METHODS

The study involved 37 individuals (university students, 18 ± 1.1 years old; 27 females and 10 males).

To determine verbal and figurative (visual-spatial) components of intelligence, the Amthauer intelligence structure test was used, i.e., mean values of the two verbal (subtests 2 and 3) (*IQv*) and two non-verbal visual-spatial tasks (subtests 7 and 8) (*IQs*) performance. Non-verbal figurative creativity was assessed using the Torrance "Circles" and "Incomplete figures" subtests, while the verbal one was assessed using the Guilford's Alternative Uses Test and creation a meaningful sentence with the inclusion of three stimulus words (nouns from distant semantic categories). The originality of response indices upon the performance of the first three methods were calculated on the basis of the corresponding database as reciprocal of a number of the same ideas [35]. The sentence originality was assessed by three trained experts with experience in working with this technique (Cronbach's α for the estimates was 0.82).

Table 1. Descriptive statistics for the intelligence and creativity indices

Variable	Mean	*SD*	Minimum	Maximum
Intelligence				
Verbal (*IQv*)	105.3	6.2	90.5	114.5
Figural (*IQs*)	105.9	6.9	90.5	124.0
Originality				
Circles (Oc)	1.2	1.2	0.1	5.8
Incomplete figures (Oif)	3.4	1.4	0.8	7.1
Unusual use (Ouu)	1.4	1.2	0.1	4.7
Sentence making (Osm)	3.7	2.4	0.0	9.8

IQv, verbal component of intelligence; *IQs*, visual-spatial component of intelligence; Oc, originality index upon the performance of the "Circles" subtest; Oif, originality index upon the performance of the "Incomplete figures" subtest; Ouu, originality index upon the performance of the "Unusual use" subtest; Osm, originality index upon the performance of the "Sentence making" subtest.

EEG recording in the state of quiet wakefulness with eyes closed was performed using Mitsar-201 equipment and software (Russia) through 19 leads (Fp_1, Fp_2, F_7, F_3, Fz, F_4, F_8, T_3, C_3, Cz, C_4, T_4, T_5, P_3, Pz, P_4, T_6, O_1, O_2) arranged according to the 10/20 system with an integrated ear reference electrode and ground electrode in lead *Fpz*. The electrode resistance was less than 5 kOhm. The bandpass filter, 50/60 Hz; high- (HP) and low-pass (LP) filter parameters, 0.53 and 50 Hz, respectively. For the analysis of brain activity, 2-s artifact-free EEG segments with an overlap of 50% with a total duration of 60 s were selected. The sampling rate was 250 Hz. For each electrode site, the EEG spectral density was calculated using the fast Fourier transform method in six frequency ranges: Δ (1–4 Hz), θ (4–7 Hz), α_1 (7–10 Hz), α_2 (10–13 Hz), β_1 (13–20 Hz), and β_2 (20–30 Hz). For statistical analysis, the natural logarithm of EEG power values in the Δ- and β_2-ranges was used according to the goal of the study.

Statistical data treatment was performed using the Statistica 13.3 (*SN: JPZ912J057923CNET2ACD-K*) licensed software package.

RESULTS

Table 1 shows the results of testing the intelligence and creativity indices.

Cluster organization of the creativity and intelligence indices. At the first step of data analysis, organization of the creativity and intelligence indices was examined by means of agglomerative hierarchical clustering of pre-normalized data (normalization was performed by dividing by the mean value). Evaluation of the different methods showed that the best clustering was provided by Ward's method with the Euclidean metric (Fig. 1). Similar structure of clusters that combine the intelligence and creativity indices is provided by complete-linkage clustering, which is based on determining the maximum pairwise distances between objects in different clusters. Since Ward's method is based on determining minimum variance in hypothetical clusters, the formed hierarchical structure of intelligence and creativity indices can be considered optimally stable for interpreting the result.

The cluster structure shown in Fig. 1 indicates the closest relationship between *IQs* and figural originality upon the performance of the "Circles" subtest, and grouping this cluster together with *IQv* and the verbal originality measure for the "Alternative Uses Test" into a common cluster (cluster 1). The originality of response indices upon the performance of the other two subtests ("Incomplete figures" and "Sentence making") form a cluster separate from the first group of variables, which points to the different strategy for finding a solution to the problem (cluster 2).

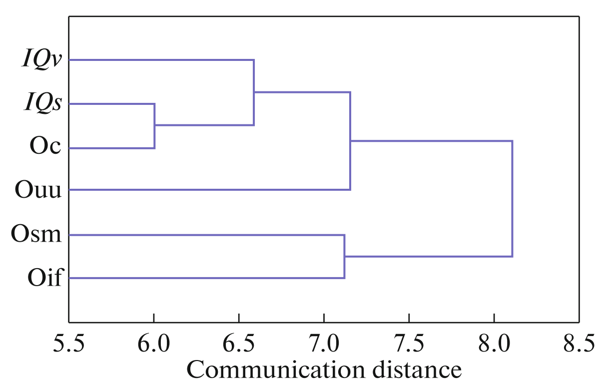

Fig. 1. Dendrogram of proximity measures for the indices of verbal and non-verbal components of intelligence and creativity according to Ward's clustering. *IQv*, verbal component of intelligence; *IQs*, visual-spatial component of intelligence; Oc, originality index upon the performance of the "Circles" subtest; Ouu, originality index upon the performance of the "Unusual use" subtest; Oif, originality index upon the performance of the "Incomplete figures" subtest; Osm, originality index upon the performance of the "Sentence making" subtest.

Table 2. Quantitative composition and normalized intelligence and creativity indices in two groups formed on the basis of the results of cluster analysis using the *K-Means* method

Group	*n*	M (*n*)	F (*n*)	*IQv*	*IQs*	Oc	Ouu	Oif	Osm
GR_{CIQ}	17	5	12	0.51	0.39	0.47	0.36	–0.26	–0.35
GRc	20	5	15	–0.33	–0.27	–0.33	–0.35	0.19	0.39
P	n/d	n/d	n/d	0.02	0.05	0.001	0.02	0.10	0.01

n, total number of participants; M (*n*), number of males; F (*n*), number of females. For other designations, see Table 1.

For further analysis of the EEG data, samples were formed by clustering of the intelligence and creativity indices with the help of the *K-Means* algorithm, which made it possible to separate two groups that differed in the values of the considered indices. Composition of these groups was adjusted based on the results of hierarchical clustering. In particular, GR_{CIQ} consisted of individuals who showed relatively high scores in the "Circles" and "Alternative Uses Test" (included in cluster 1), and GR_C consisted of individuals with relatively high scores in the "Incomplete figures" and "Sentence making" subtests (included in cluster 2).

Analysis of variance of all creativity indices showed the effect of GROUP factor ($F_{5,166} = 6.85$; $P < 0.0001$; $\eta^2 = 0.17$). A two-way ANOVA with independent variables, SEX (2) and GROUP (2), performed for each measure of intelligence and creativity revealed the effect of only GROUP factor ($2.69 < F_{1,33} < 12.5$, $0.001 < P < 0.1$) with higher *IQ* values, Oc and Ouu in GR_{CIQ}, versus relatively low *IQ* values, but higher Oif and Osm values in GR_C (Table 2).

Thus, the objective of further study was to elucidate the EEG correlates of creativity, which differed in groups formed according to the identified different strategies for finding a solution to the problem. The analysis limited us to only Δ- and β-rhythms, since their informative value as predictors of non-verbal creativity and verbal intelligence was previously demonstrated [32].

Cluster organization of Δ- *and* β_2*-rhythms in groups differing in the structure of creativity and intelligence*. To elucidate the patterns of frequency-spatial organization of low- and high-frequency oscillations in the selected groups, GR_{CIQ} and GR_C, Ward's hierarchical agglomerative clustering with a Euclidean metric was also used. Figure 2 shows the dendrograms of formed clusters obtained for these groups for the Δ-rhythm, and Fig. 3, for the β_2-rhythm.

According to the Δ-rhythm cluster organization, two clusters were distinguished in both groups. However, GR_{CIQ} was characterized by greater distance of the cluster representing the anterior cortical areas with the leading role of oscillations in F_8. At the same time, in GR_C the resulting clusters were similar in terms of connectivity, and in the combination of the anterior cortex areas the leading role belonged to F_7 and F_8 (Fig. 2) (the specificity of the inclusion of these sites in the clusters identified for GR_{CIQ} and GR_C was proved by an additional cluster analysis of the Δ-rhythm only for the anterior part of the cortex).

Regional organization of the β_2-rhythm is represented by two clusters in GR_{CIQ} (Fp_1 and Fp_2 form one cluster, the remaining electrode sites form the second

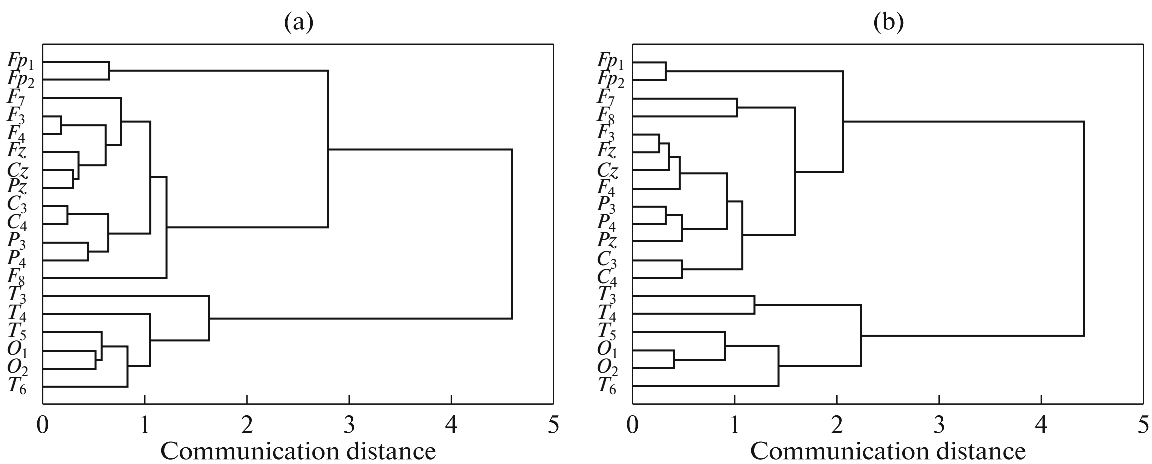

Fig. 2. Dendrograms of Δ-rhythm clusters formed using Ward's method and representing groups that differ in the creativity organization: correlated with intelligence (a) and not correlated with intelligence (b).

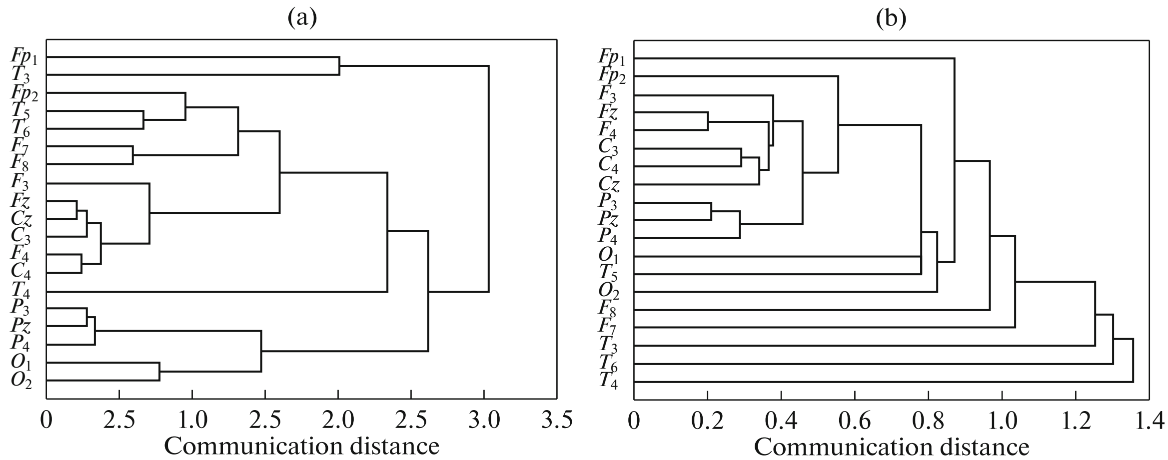

Fig. 3. Dendrograms of β_2-rhythm clusters formed using Ward's method and representing groups that differ in the creativity organization: correlated with intelligence (a) and not correlated with intelligence (b).

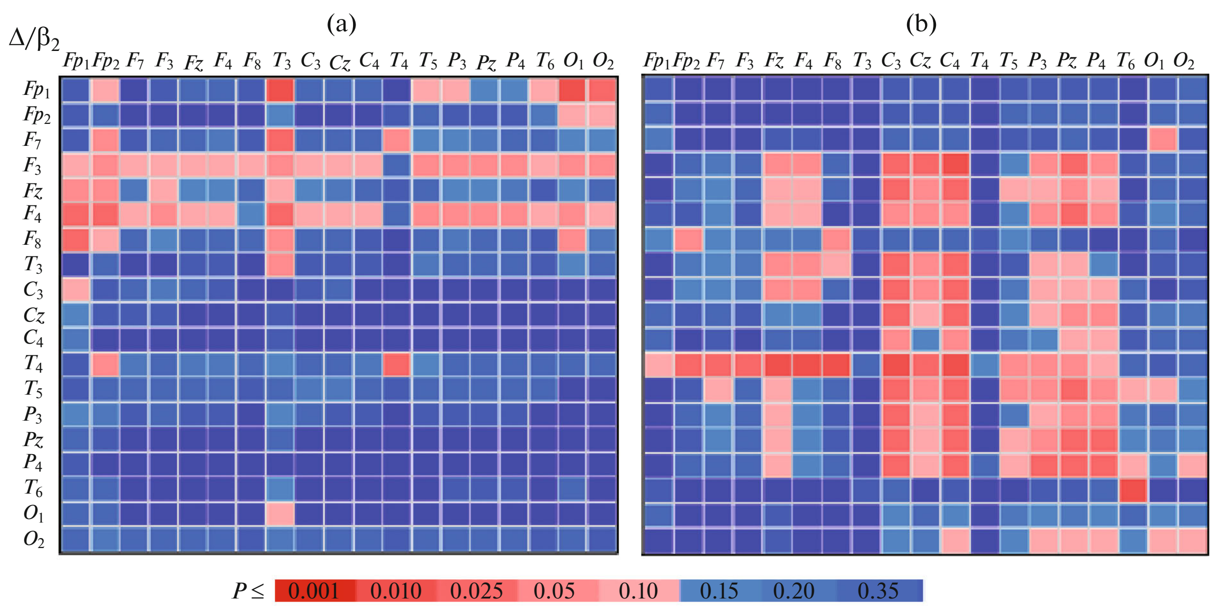

Fig. 4. Correlation maps between Δ- (vertical leads) and β_2 (horizontal leads) rhythms for groups that differ in the organization of creativity: correlated with intelligence (GR_{CIQ}, a) and not correlated with intelligence (GR_C, b).

cluster) and four clusters in GR_C (sites T_3, T_6, and T_4 reflect three separate clusters, and all other sites are included into another, common cluster) (Fig. 3). Moreover, the leading role in grouping of two β-rhythm clusters in GR_{CIQ} is played by the region represented by T_4, and in GR_C, by F_7, F_8 and Fp_1.

To determine the degree of interaction between high-frequency β_2 and low-frequency Δ biopotentials in GR_{CIQ} and GR_C, a correlation analysis was performed, the results of which are shown in Fig. 4 ($0.50 < r < 0.63$ at $0.008 < P < 0.05$; the sites for the Δ-rhythm are shown vertically, and the sites for β_2 are shown horizontally).

The data indicate that the differences between groups are represented by more pronounced associations between the Δ-rhythm in the frontal cortex and β_2-oscillations in the posterior cortex for GR_{CIQ} (Fig. 4a), while GR_C is characterized by more widely distributed correlations of β_2- and Δ-rhythms with the concentration in central-parietal cortical areas (Fig. 4b).

Thus, it can be concluded that the two selected groups of study participants, differing in the level of intelligence and originality of responses while performing the tasks which require the rejection of stereotypical ideas (GR_{CIQ}) or solve a problem under conditions of a given variety of stimuli (GR_C), are characterized by different forms of regional organization of Δ- and β_2-rhythms and their relationships. In GR_{CIQ}, two clusters were identified in each frequency range, representing different forms of association of the anterior and posterior cortical regions, reflected in the correlation of low-frequency biopotentials of the frontal cortex and the generalized high-frequency activity of β-activity. GR_C is distinguished by regionally more differentiated clustering of β_2-activity at its diffusely distributed correlation with the Δ-rhythm while the exclusion of anterior frontal areas.

DISCUSSION

The results indicate that the stimulus material itself, despite the general instruction "to be original," determines the strategy for finding a solution to the problem, even to a greater extent than its verbal or figural nature. Repetitive stimuli (circles or an ordinary object) contribute, first of all, to the generation of stereotyped responses. Therefore, in order to reject them and continue the search with critical assessment of the ideas, arising during the search, such pre-tuning of resting-state brain activity is required, in which the prefrontal cortex is involved (Figs. 2a–4a). This situation is characterized by a combination of originality and *IQ* indices (Fig. 1). Under the conditions of testing creativity using a variety of stimuli belonging to different semantic categories, the response strategy in a widely represented network of associations is preferable for successful completion of a task, which is reflected by the dominance of diffusely associated areas of the posterior cortex (Figs. 3b, 4b). It can be suggested that such functional association of different cortical regions is provided by the synchronization of neural networks at the Δ- and β-range frequencies. In particular, with the dominance of prefrontal regions in the case of a tendency to the strategy of critically conditioned rejection of the stereotype, but temporo-parietal-occipital regions, in the cases of the given stimuli causing actualization of distant associations. It is noteworthy that in the latter case, there is a relatively greater effect of synchronization of the Δ- and β_2-rhythm amplitudes in the sites of the right hemisphere (T_4, O_2), while in the first case, of the left hemisphere (Fp_1, F_7). That is, the observed effect of a change in hemispheric dominance associated with creativity [20–22] can be explained by individual preferences in using the strategies of "intellectual" or "spontaneous" realization of divergent thinking, accompanied by a shift in activity in the FPN and DMN upon problem solving [23]. The data testify to the importance of the resting-state FPN and DMN and are in good agreement with data on different regional associations of creativity components, i.e., fixation resistance, with frontotemporal areas, and the originality, with DMN [20].

The "intellectual" strategy is understood as an internally directed search for a response, the originality of which is determined by intellectual abilities (resources of knowledge and logical thinking), while the "spontaneous" strategy is defined as the insurance of divergent thinking due to a given variety of stimuli. The success of divergent thinking is mediated by the involvement of different components of intelligence, the combination of which makes it possible to predict about 46% of neural networks involved in creativity [5], and the reason for its failure may be the lack of desire to search for information [36].

According to the literature data, the biopotentials of the Δ-range are considered as an indicator of the motivational component of activity that modulates functional activity of neural networks [37, 38], while β-activity reflects the information load and factors of cognitive control reorganization through the FPN functions [29, 39, 40]. In this case, the revealed regional specificity of the correlation patterns of these rhythms in Gr_{CIQ} and GR_C can be interpreted as motivational pre-tuning of flexible reorganization of the selective processes in order to search for an original idea, based on executive control or a system of distant semantic associations, respectively.

Thus, analysis of the resting state EEG makes it possible to assess the individual resources of the reorganization of the brain structures depending on the conditions for creativity testing, which first of all require the flexibility of thinking or fluency in the search for ideas. It seems likely that due to the summation of such different strategies for solving a problem, in psychometric creativity testing, different forms of relationships between originality, fluency, and flexibility are observed [41, 42]. This fact of different ways of achieving a result is emphasized in the dual pathway to creativity model, i.e., as a function of flexible thinking and perseverance [43], or the association of originality and flexibility indices not only with different brain structures, but also with their multidirectional associations [44, 45]. Thus, as one of the factors of the observed diversity in the interaction of brain structures in the analysis of creativity [4, 8–11], different testing conditions should be considered, since the tasks most often used in both EEG and fMRI studies are "Alternative Uses Test" or "Incomplete figures" are different in nature (verbal and non-verbal, respectively) and, as was demonstrated in the present study, require different strategies for finding an answer.

CONCLUSIONS

The revealed frequency-spatial patterns of Δ- and β_2-rhythms and their relationships reflect pre-tuning of functional cortex activity to use different strategies for searching for an original idea in creativity testing. The combination of low-frequency biopotentials of the frontal cortex and generalized high-frequency β-activity can be associated with the strategy of an "intelligent" search for an original answer under the pressure of stereotypical decision. Differentially presented clustering of β_2-activity with its more diffusely distributed correlation with the Δ-rhythm with the exclusion of the anterior frontal areas reflects the search for a solution based on spontaneous, less controlled associations.

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COMPLIANCE WITH ETHICAL STANDARDS

Conflict of interest. The authors declare the absence of obvious and potential conflicts of interest related to the publication of this article.

Statement of compliance with standards of research involving humans as subjects. All studies were carried out in accordance with the principles of biomedical ethics formulated in the Declaration of Helsinki of 1984 and its subsequent updates, and approved by local ethics committee of the Faculty of Humanities, Novosibirsk State Technical University (Novosibirsk). Each participant in the study provided a signed voluntary written informed consent after explaining the potential risks and benefits, as well as the nature of the upcoming study.

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