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Electroencephalographic correlates of the activity of the frontoparietal system as predictors of verbal intelligence and non-verbal creativity

Olga M. Razumnikova*, Ksenia D. Krivonogova
Novosibirsk State Technical University, Novosibirsk, Russian Federation
Corresponding author. * E-mail: razoum@mail.ru

Abstract

Introduction. It is known that the frontoparietal system is involved in both intellectual and creative functions, but no consensus has been achieved on the issue of how these functions and the associated activity of the frontoparietal parts of the brain interplay and reflect each other. The purpose of this study was to identify patterns of neuronal oscillations, which could be predictors of verbal or figurative components of intelligence and/or imaginative creativity.

Methods. The activity of the frontoparietal cortex was analyzed using multichannel electroencephalography (EEG) technique. The study enrolled 37 university students. The EEG baseline power values of 6 frequency bands, from delta to beta2 were analyzed in comparison with the verbal (IQv) and figurative (IQf) components of intelligence assessed using the Amthauer technique and with the imaginative originality when performing the Torrance subtest "Incomplete figures task" (IFT).

Results. When comparing groups with high or low IQv or IFT rates, the following general effects were established: asymmetry in the activity of anterior and posterior-frontal regions in the beta1 frequency band and higher power values of the delta rhythm in frontal regions of the cortex in individuals with higher IQv rate, and in the central-parietal cortex in individuals with higher imaginative originality rates, respectively, along with higher values of the alpha1 rhythm in the central and the alpha2 rhythm in the frontal areas of the cortex. Regression models calculated for IFT and IQv were similar, delta rhythm power values in the frontal leads of the left hemisphere being the main predictor of intellectual and creative abilities.

Discussion. The similarity of the regression models for IFT and IQv with more pronounced differences in frequency and regional representation of the EEG correlates of the imaginative originality should be considered as evidence that intelligence (and the structures associated with it) is a necessary but not sufficient condition for creativity. The detected frequency-spatial relationship between the IFT and IQv may arise from the similar organization of executive control over the imaginative task performance.

Keywords

frontoparietal system, electroencephalography, delta oscillations, alpha oscillations, beta oscillations, verbal intelligence, non-verbal creativity, imaginative originality

Highlights

► The background activity of the frontal areas of the cortex in the low-frequency delta and high-frequency beta bands is a predictor of both non-verbal creativity and verbal intelligence.

► With the general similarity of the regression models of non-verbal creativity and verbal intelligence, in individuals with higher imaginative originality rates additional changes in the power of alpha1, alpha2, and beta2 oscillations have been revealed.

► The background activity of the frontoparietal system associated with imaginative originality is represented more broadly both in the frequency range and brain regions in comparison with EEG correlates of verbal intelligence.

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Introduction

Recent intensive studies neurophysiological correlates of creativity revealed the key importance of the frontoparietal system functions associated with the search for new ideas or executive control when choosing an original solution to the problem (Beaty, Benedek, Wilkins, & Jauk, 2014; Beaty, Seli, & Schacter, 2019; Gulbinaite, van Rijn, & Cohen, 2014; Heinonen, Numminen, Hlushchuk, Antell, Taatila, & Suomala, 2016). On the other hand, the interaction of these brain regions is considered as the neurophysiological basis for the implementation of one's intellectual abilities (Beaty et al., 2014; Jung & Haier, 2007; Hearne, Mattingley, & Cocchi, 2016; Lee et al., 2006; Pamplona, Neto, Rosset, Rogers, & Salmon, 2015), which is not surprising, given the need for executive control of problem-solving during intelligence testing. However, using the recent technique of diffusion tensor imaging and tractography a specialization in the interaction of the structures of the frontoparietal system and the brain default mode network (DMN) associated with intelligence or creativity was revealed. Intelligence was shown to be represented by a system for "easy" achievement a functional state with activation of the right upper parietal region, while the left retrosplenial cortex has low integration abilities; creativity at that, as evaluated with verbal subtests

of Torrens, turned out to be represented by a system of "elaborate" switching of connectivity of cortical regions with a center in the right dorsolateral prefrontal cortex with high integration abilities of the sensorimotor cortex (Kenett, 2018). Moreover, the integral indicator of the originality of responses was characterized by a connectivity "hub" region in the posterior part of the superior temporal gyrus, suggesting that speech functions were involved in the generation of ideas. Analysis of the brain activity related to non-verbal creativity, along with a widespread bilateral neuronal network, demonstrated the dominance of the left hemisphere, including the left dorsolateral prefrontal cortex (Aziz-Zadeh, Liew, & Dandekar, 2013) or the left anterior singular cortex (Hahm, Kim, Park, & Lee, 2017), which are considered to be necessary to find an original solution to a problem.

Traditional methods of EEG analysis continue to be widely used to investigate mechanisms of the functional interaction of cortical areas, along with modern functional magnetic resonance imaging technique (fMRI) (Herrmann, Strüber, Helfrich, & Engel, 2016; Stevens & Zabelina, 2019). As an indicator of activation or inhibition processes in neuronal networks among frequency bands of biopotentials alpha rhythm is often preferred (Benedek, Jauk, Sommer, Arendasy, & Neubauer, 2014; Fink & Benedek, 2014; Lustenberger, Boyle, Foulser, Mellin, & Fröhlich, 2015; Razumnikova, 2007). Creativity-related changes in the synchronization of alpha biopotentials in the frontal areas noted by different authors turn out to be dependent on both the level of intelligence and creativity of experiments subjects (Benedek et al., 2014; Lustenberger et al., 2015; Razumnikova, 2009a; Dikaya & Dikii, 2015; Nagornova, 2007; Benedek, Bergner, Könen, Fink, & Neubauer, 2011). The positive relationship between intelligence and creativity have been confirmed by the results of both psychometric and neurophysiological studies (Jauk, Benedek, Dunst, & Neubauer, 2013; Karwowski et al., 2016; Nusbaum & Silvia, 2011; Preckel, Holling, & Wiese, 2006). However, there is no consensus about the "threshold" effect in the ratio of these psychometric constructs (Jauk et al., 2013; Nusbaum & Silvia, 2011; Preckel et al., 2006) or on regional specificity of this effect (Benedek et al., 2014; Razumnikova, 2009b; Arden, Chavez, Grazioplene, & Jung, 2010; Jung, Mead, Carrasco, & Flores, 2013; Pidgeon et al., 2016). This study based on structural approach with latent variables investigated roles of three specific components of the executive system: information resources updating, switching, and inhibition, as well as their general and differential relations with fluid intelligence and divergent thinking abilities. It turned out that inhibition and updating of working memory are predictors of creativity; the latter component also determines the variability of IQ (Benedek et al., 2014). The balance between the background activity of the frontal and posterior cortex is considered as a basis of choosing an individual cognitive style, including the preferences for an insight or an analytical strategy for solving problems (Benedek et al., 2014; Erickson et

al., 2018; Kounios et al., 2008). Predictors of this balance are low-frequency theta, alpha, and high-frequency beta oscillations (Heinonen et al., 2016; Stevens & Zabelina, 2019; Solomon et al., 2017).

Earlier, in another study using a heuristic problem as a model of creativity it was shown that individuals with high intelligence and creativity rates are characterized with enhanced interaction of neuronal ensembles in the anterior cortex and left hemisphere in contrast with those with lower rates of these parameters (Razumnikova, 2009a). This conclusion was drawn based on the analysis of EEG coherence, and the effects of the interaction of the factors "creativity" and "intelligence" were presented in a wide range of frequency bands from theta1 to beta 2, for the imaginative intelligence parameters, predominantly.

According to the classical conception of the two- stage creative thinking, the generation of ideas is associated with diffuse attention and bottom-up neuronal processes, and their evaluation with focused attention and executive control, i.e. top-down processes (Jung et al., 2013). These processes are ensured by the cooperation of the DMN and the executive control system (Beaty et al., 2014; Benedek et al., 2014). Since the state of the DMN reflects a variety of individual personality characteristics, including intelligence or creativity (Beaty et al., 2019; Li, Yang, Zhang, Li, & Qiuc, 2016; Takeshi, Aihara, Shimokawa, & Yamashita, 2018), it is not surprising that the unique interaction of these neuronal structures creates variable patterns of the activation-inhibition processes, which are reflected in the frequency-spatial EEG characteristics. In this regard, the purpose of the study was to elucidate such patterns of neuronal oscillations in the frontal and central areas of the parietal parts of the brain which are associated with verbal or visual-spatial components of intelligence and creativity and could serve as their level predictors.

Research hypotheses:

– background activity of the frontoparietal system of the brain is associated with psychometric indicators of intelligence and creativity with a broader frequency-spatial representation for imaginative originality;

– models for describing intelligence and creativity have similar EEG predictors of the activity of the frontal cortex, and regionally and frequency-specific predictors.

Methods

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

To determine the verbal and imaginative (visual-spatial) components of intelligence, we used the Amthauer intelligence structure test. Imaginative creativity was assessed using the Torrens subtest "Incomplete figures task". The

originality index was calculated with a computerized technique as a number inverse to the number of drawings with identical ideas to those stored in the database (Razumnikova, 2002).

EEGs were recorded in subjects in a state of quiet *wakefulness* with eyes closed using Mitsar-201 hardware and software in the 19 leads (Fp1, Fp2, F7, F3, Fz, F4, F8, T3, C3, Cz, C4, T4 , T5, P3, Pz, P4, T6, O1, O2), arranged according to the 10/20 system, with an integrated reference ear electrode. To analyze the brain activity, 2-second artifact-free EEG segments were selected with a total duration of 60 sec. The EEG spectral density was calculated in each lead in six frequency bands: delta (1–4 Hz), theta (4–7 Hz), alpha1 (7–10 Hz), alpha2 (10–13 Hz), beta1 (13–20 Hz) and beta2 (20–30 Hz), using the fast Fourier transform technique. For statistical analysis, the natural logarithm of the EEG power values was used.

Results

The intelligence and originality rates when performing figurative creativity tasks in the groups of males and females did not differ significantly ($0.40 < p < 0.65$), and further analysis was performed for the whole series of subjects. Correlation analysis revealed positive relationship between IQv and IQs rates ($r = 0.39$, $P < 0.015$). Significant correlations with the rates of the imaginative originality were not found for IQv nor IQs ($r = 0.25$ and 0.06, respectively).

To further analyze the EEG correlates of IQv, IQs, and creativity, subjects were classified into groups with high (IQv1, IQs1, IFT1) or low (IQv0.IQs0.IFT0) ratings of intelligence and imaginative originality, based on the average rates for each parameter. Characteristics of the groups and the rates of intelligence and creativity are summarized in Table 1 (there was a significant intergroup difference: $6.78 < t < 9.33$, $P < 0.00001$).

Table 1
Characteristics of groups with high or low rates of intelligence or creativity for comparative analysis

Parameter	High rates		Low rates	
	n	values	n	values
Verbal IQ	20	109,2 ± 3,3	17	100,0 ± 5,0
Visual and spatial IQ	17	112,4 ± 4,6	20	100,9 ± 3,7
Originality of imaginative creativity	14	2,6 ± 0,6	23	4,9 ± 0,8

According to the purpose of the study the activity characteristics in the frontal and central parietal (CPariet) cortical regions for each frequency band were analyzed with one-way ANOVA test for every pairs of independent factors: IQv1/IQv0, IQf1/IQf0 or IFT1/IFT0. The effects revealed in the IQv or IFT analyses are summarized in Table. 2. For IQf no significant effects were detected.

Table 2
Results of the analysis of variance between groups with high or low rates of intelligence or creativity parameters

Parameter	Frequency	Area	F	df	P	Effects
IQv	Delta	Front	4,67	1.35	0,04	IQv1 > IQv0
IFT			3.53		0.07	IFT1 > IFT0
		CPariet	3.91		0.05	
IFT	Alfa1	CPariet	2.62	5.175	0.03	IFT1 > IFT0 in C3, Cz, C4
	Alf 2	Front	2.15	6.210	0.05	IFT1 > IFT0 in Fz, F4, F8
IQv	Beta1	Front	2.62	6.210	0.02	IQv0 > IQv1in Fp1, but IQv1 > IQv0 in Fp2, F3, Fz, F4
IFT			2.78		0.01	Fp1: IFT0 > IFT1, Fp2, F3, Fz, F4: IFT1 > IFT0
IFT	Beta2	Front	2.50	6.210	0.03	Fp1: IFT0 > IFT1, Fz, F4: IFT1 > IFT0

Notes: Front, frontal cortical areas, CPariet*, central parietal cortical areas*

Within the delta frequency band a general effect for IQv was revealed: in the frontal cortex the power of these low-frequency oscillations was higher in the IQv1 group than in the IQv0 group. A similar effect was noted for the frontal areas as a non significant trend, and for the central parietal areas as a significant difference between groups with different levels of imaginative originality. Within the alpha frequency band the higher EEG power values differed depending on regions: the power values for the alpha1 band they were significantly higher for the IFT1 vs the IFT0 group in central regions of the cortex, and for the alpha2 band they were higher in the frontal regions with dominance of the right hemisphere (Fz, F4, F8).

Within the beta1 frequency band EEG power values were lower in the high IQv and high imaginative originality groups as compared to the IQv0 and IFT0

groups in the left anterior-frontal lead with inversion of this effect for all other areas of the prefrontal cortex (Fig. 1). The same asymmetry effects for beta2 oscillations in the frontal cortex were also revealed between the IFT groups, but not between the IQv groups (see Table 2).

Thus, ANOVA results revealed the similarity of the activation effects in the frontal cortex delta and beta1 bands associated with verbal intelligence and imaginative originality levels. At the same time, it should be noted that the EEG changes associated with creativity as opposed to those associated with IQv are presented more broadly both for regions involved (posterior cortex), and for frequency bands (alpha1.2 and beta2 oscillations).

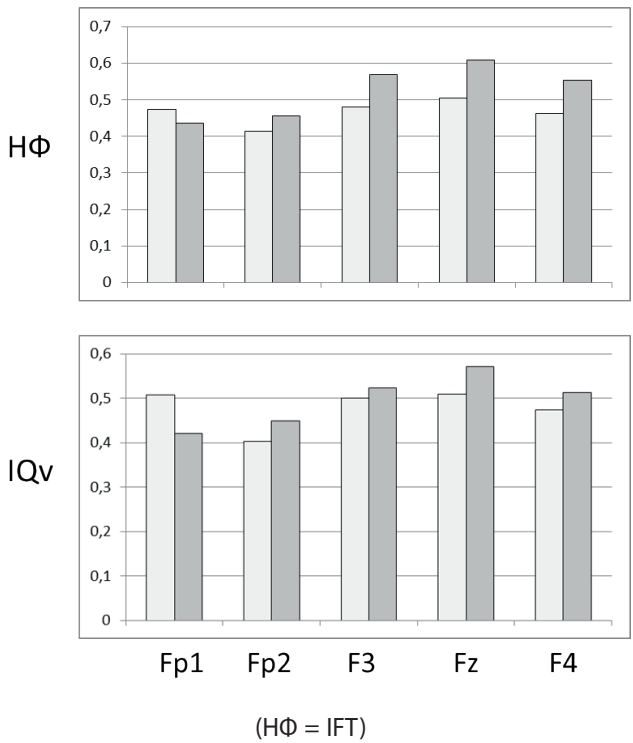

Figure 1. Regional characteristics of the beta1 rhythm power values in the frontal leads depending on the level of the imaginative originality (IFT) or verbal intelligence (IQv)

The functional role of the detected intergroup differences in the background EEG power values has been analyzed using the regression analysis: imaginative

originality or verbal intelligence were considered as independent variables, the power values for frequency bands and leads identified at the previous analysis stage were chosen as dependent variables. Linear regression with stepwise addition of dependent variables was used.

The correlation analysis of EEG indicators confirmed the absence of multicollinearity. The opposite correlations in different groups were found for the delta and beta1,2 rhythms power in the anterior frontal leads: positive in the IFT0 group and negative in the IFT1 group ($0.07 < P < 0.04$). With no vital differences in the delta and beta1 rhythms between the IFT0 and IFT1 groups in other cortical areas the average delta or beta2 rhythms power values in the frontal cortex were more stable for the IFT1 group compared to the IFT0 group ($r = 0.63$, $p < 0.02$ and $r = 0.36$, $p < 0.1$, respectively). This effect of a better coherence between the delta and beta2 rhythms in the IFT1 group was observed in the leads F3, F7, F4, Cz, C3 ($0.52 < r < 0.61$, $0.02 < p < 0.05$).

As for the IQv groups, correlation analysis of the average rhythm power values revealed a significant association between delta and beta2 rhythms in the back cortex for the IQv1 group without regional lead-depending specificity of this effect. For the beta1 band rhythms positive correlation of rhythms in the IQv0 group was observed generalized throughout all leads except the anterofrontal ones; in the IQv1 group, the correlations of delta and beta1 oscillations were significant only in the parietal regions in the leads F3, F4, F8.

The best models for IFT or IQv obtained in the regression analysis of the delta and beta rhythms are shown in Table 3. The correlation coefficient between the selected dependent variables, power values of the delta and beta1 or beta2 rhythm, turned out to be lower than 0.27, which rules out the effect of multicollinearity of the dependent variables. Contribution of the power values of alpha 1.2 oscillations did not improve the descriptive possibilities of the regression models for IFT.

According to the regression models, about 5% of the IFT dispersion can be predicted either by the average power values of the delta rhythm in the frontal areas of the cortex, or values in the leads F3 or F4. Beta1 or beta2 rhythm values in the anterofrontal lead of the left hemisphere added to the regression model increased its descriptive possibilities (R^2 increased up to 16–17 %), however, contribution of the of high-frequency oscillations power values was not significant (see Table 3).

The regression models for IQv turned out to be similar to those obtained for IFTs, with the only exception that the F7 lead values substituting for the F3 ones: the delta rhythm power in the F7 lead predicts about 16% of IQv variability. The introduction of beta power values into the regression analysis increased the R^2 up to 21–23%, however, just as in the models for IFTs, these high-frequency IQv predictors are not significant ($0.08 < p < 0.16$).

Table 3
Main parameters for regression models for the originality (IFT) and the verbal intellect (IQv) rates

Frequency bands	Area	F	df	p_F	R^2	β	t	p_t
IFT								
Delta	Front	4.04	1.35	0.05	0.10	0.32	2.01	0.05
	F3	4.29		0.05	0.11	0.33	2.07	0.05
	F4	4.11		0.05	0.10	0.32	2.03	0.05
Delta	F3	3.57	2.34	0.04	0.17	0.41	2.50	0.02
Beta1	Fp1					–0.26	–1.62	0.11
Delta	F3	3.24		0.05	0.16	0.36	2.29	0.03
Beta2	Fp1					–0.23	–1.44	0.16
IQv								
Delta	Front	3.39	1.35	0.07	0.09	0.30	1.84	0.07
	F7	6.58		0.01	0.16	0.40	2.56	0.01
	Fp1	3.02		0.08	0.09	0.28	1.74	0.08
	Fp2	3.25		0.08	0.09	0.29	1.80	0.08
Delta	F7	4.41	2.34	0.02	0.21	0.43	2.78	0.01
Beta1	Fp1					–0.22	–1.43	0.16
Delta	F7	5.14		0.01	0.23	0.41	2.70	0.01
Beta2	Fp1					–0.27	–1.80	0.08

Discussion

Findings obtained by the intergroup comparison are consistent with the idea of the intelligence (and the structures associated with it) as a necessary but not sufficient condition for creativity (Karwowski et al., 2016). Moreover, the necessary condition for imaginative creativity turned out to be the verbal intelligence, because of the involvement of speech functions both in the ideas generation (Kenett et al., 2018) and in the organization of executive control when performing a task. These two components of creativity might be associated with different oscillatory components of the background activity of the cortex: executive control relating to the delta activity (Knyazev, 2007, 2012), and speech functions relating to the beta1 activity (Pulvermuller, Birbaumer, Lutzenverger, &

Mohr, 1997). An increase in the power of biopotentials detected in the alpha1,2 frequency band in subjects with high imaginative originality supports the concept of "pre-setting" of the background state of the brain (Kounios et al., 2008), facilitating realization of internal attention and inhibition processes in divergent thinking (Benedek et al., 2011).

The more pronounced representation of the synchronization effect for delta oscillations in the IFT1 compared to the IFT0 group, where it covers not only the frontal, but also the central parietal parts of the cortex, reflects the potential possibility to connect to the distributed neuronal network of the multimodal information as a resource for the creative activity. Indeed, using fMRI, the interaction of the frontoparietal system and DMN has been shown to be integral to generate conceptually new solutions when performing tasks testing imaginative creativity (Christensen, Benedek, Silvia, & Beaty, 2019). The effective coordination of neuronal ensembles of this distributed system requires synchronization of the slow wave activity, according to our data and the results of an earlier study, where, in addition, a positive relationship between delta oscillations and originality of divergent thinking were observed (Boot, Baas, Mühlfeld, de Dreu, & van Gaal, 2017).

The similarity of the obtained models for ITF and IQv can be considered as a potential ability to use different strategies, both insight and analytical ones when performing an imaginative creative task, moreover, the ability to differentiate these cognitive strategies is supported with beta oscillations in the background EEG (Erickson et al., 2018), the power of which is an additional predictor of dispersion both for IFT, and IQv, according to the regression models.

A steady contribution to the regression models of both IFT and IQv made by the delta biopotentials in the left frontal cortical regions may reflect the ability to control the cognitive activity additionally with motivational potential (Knyazev, 2007) and to coordinate the activity of spatially distributed neuronal networks to search for an original solution, as it was noted earlier (Bhattacharya & Petsche, 2005). However, there exists evidence of an opposite reaction as well: generation of a unique image can be associated with a lower level of delta oscillations (Foster, Williamson, & Harrison, 2005). Perhaps such contradictions reflect the effect of a subjective overestimation of the task complexity which affects the balance of activation and inhibitory processes in the cortex (Razumnikova, 2009a). The regional specificity of the predictors for IFT or IQv (leads Fp1, F3, F7) is consistent with the planning functions of the left part of the dorsolateral prefrontal cortex, which part performs a targeted search for a solution to a problem (Aziz-Zadeh et al., 2013). The connectivity factor of the left part of the frontoparietal system and the anterior part of the DMN correlates positively with the originality of solutions to divergent problems (Shi et al., 2018).

An additional contribution of the beta rhythm to the model can be interpreted as part of the control of image reproduction using the associative-semantic network when performing creativity tasks. Moreover, the negative sign of the beta1,2 rhythms power values in the left anterior-frontal cortex (Fp1 lead) may be the evidence of a negative role of the accelerated image reproduction in the task with completing figures, since presented stimuli primarily bring to mind the most common stereotypical objects. This hypothesis is supported by findings on the functional importance of the left prefrontal areas for the fluent generation of ideas (Hirshorn & Thompson-Schill, 2006).

Conclusion

An analysis of the background activity of the frontal and central-parietal cortical regions in six frequency bands from delta to beta2 revealed, that only the delta and beta1 oscillations power values are predictors of both non-verbal creativity and verbal intelligence. With similar regression models of imaginative originality and the verbal component of intelligence, stratification of individuals by imaginative creativity levels reveals associated differences in power values of the alpha1, alpha2, and beta2 frequency bands, which are represented not only in the frontal but also in the central parietal cortex. Identified EEG correlates of verbal intelligence and imaginative creativity suggest that the relationship between intelligence and creativity is mediated by the frontal system of executive control of the cognitive activity.

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