STUDY OF THE RELATIONSHIP BETWEEN THE SPATIAL ORGANIZATION OF CEREBRAL CIRCULATION AND THE CONTROL OF COGNITIVE FUNCTIONS

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Abstract. The purpose of the study was to study the fronto-occipital organization of cerebral circulation during short-term mental stress, as well as to study the relationship between the spatial organization of cerebral circulation during mental stress and the effectiveness of behavior control. In this work, attention was paid to potential typological characteristic – fronto-occipital asymmetry of cerebral circulation. Known data suggest a relationship between changes in the spatial distribution of cerebral circulation and the productivity of mental activity and the effectiveness of behavior control. Using the method of rheoencephalography, 40 students (aged 19–23 years) studied the parameters of cerebral circulation during mental stress (GO/NOGO test). The stimulus material was presented on a monitor using the PsychoPy program. The number of errors was estimated. The rheoencephalogram was recorded using the «Reo-Spectrum» device. The spatial organization of pulse blood supply in the basin of the internal carotid and vertebral arteries in the initial state and during mental stress was assessed by the fronto-occipital gradient. With a short-term mental load, students showed an increase in both general and particular fronto-occipital gradients. A negative correlation was established between the increase in the right-diagonal fronto-occipital gradient (reactive control axis) in the first minute of the mental load and the number of errors in the GO/NOGO test. The prospects of using the fronto-occipital organization of cerebral circulation to predict the effectiveness of mental activity are discussed.

Keywords: mental activity, information load, behavior control, GO/NOGO test, rheoencephalography.

List of Abbreviations

Reo – Rheoencephalography
RI – rheographic index
FM – Fronto-mastoid abduction
OM – Occipito-mastoidal abduction
FOG – Fronto-occipital gradient

Introduction

The frontal regions of the cerebral cortex play a key role in human mental activity. Mental activity requires control of human behavior and increases the activation of the frontal lobes and, as a result, increases their blood supply. The interaction of the frontal regions with the occipital-parietal region is also important, especially for mental activity associated with the processing of visual information. Therefore, functional changes in the spatial organization of cerebral circulation, which can affect the efficiency of mental activity, are of particular interest.

Literary information does not allow obtaining an unambiguous picture of the functional restructuring of cerebral circulation in response to mental activity. In particular, it is known that pulse blood filling indicators are not sensitive functional markers of cerebral circulation restructuring during mental stress and give conflicting results in different studies (Bazhenov *et al.*, 2021; Chub *et al.*, 2021; Zaripov & Barinova, 2012). But the use of other functional markers gives more encouraging results, in particular, more unambiguous data on the restructuring of cerebral circulation is provided by the use of changes in vascular tone and interhemispheric asymmetry and its effect on behavior control (Prodius *et al.*, 2023). Continuing the search for functional markers of blood circulation restructuring during mental activity, attention was also paid to the fronto-occipital gradient of cerebral circulation. It is known that as the brain matures in schoolchildren, significant changes in the spatial organization of cerebral circulation are observed with an increase in the proportion of blood filling in the frontal region. To date, the formation of a hyperfrontal gradient of blood filling between the frontal and mastoid basins of the brain in children 8–11 years of age is known in the norm (Zhivotova & Voronova, 2010). A more well-known phenomenon in neurophysiology is the presence of a pronounced fronto-occipital gradient (FOG) of the alpha rhythm in adults in a state of calm wakefulness with eyes closed, most pronounced in the occipital-parietal region (Zhirmunskaya, 1991). This alpha rhythm gradient is interpreted as a predominance of brain activation in the waking state in the frontotemporal region. In addition to describing the general gradient of blood filling between the frontal and occipital parts of the brain, particular FOGs are also of interest, so the study of the fronto-occipital gradient using electroencephalography led to the isolation of the so-called «diagonal» gradients, for which a relationship with the functional state of a person has been established (Sviderskaya, 2009). Given the important role of bilateral asymmetry of cerebral circulation in the efficiency of mental activity, FOG is of interest separately for the right and left hemispheres.

Based on the above study of FOG as an indicator of the spatial organization of the blood circulation in the brain, it is of scientific and practical interest. First of all, FOG can be considered as a promising marker of functional changes during mental activity. For this purpose, one can use the indicator of pulse blood filling, recorded using rheoencephalography. In addition, the relationship of general and particular FOGs with the effectiveness of mental activity is of interest.

The aim of the work is to study the features of the spatial organization of cerebral blood flow during short-term mental stress and its relationship with the control of cognitive functions.

Materials and Methods

The studies were carried out on 40 volunteers aged 19-23 years. Informed consent signed. The study was performed in accordance with the Declaration of Helsinki (2013) and approved by the Ethics Committee of the National Research Lobachevsky State University of Nizhny Novgorod. The subjects were asked to perform an attention control task consisting of two parts of 7.5 minutes each with a short break between them. When stimulus material was presented in the form of frequent significant (GO - letter H), insignificant rare (NOGO - letter I) and insignificant rare (Novel - various signs @, ?, #, etc.) the subjects pressed certain buttons (Gomez *et al.*, 2007). Stimulus material was presented on a monitor using the PsychoPy program (Peirce, 2009). At the same time, a rheoencephalogram was recorded using the Reo-Spectrum rheoencephalograph (Neurosoft, 2008). The asymmetry coefficient of cerebral circulation in the basins of the internal carotid arteries and vertebral arteries, also known as the total fronto-occipital gradient, was calculated by the ratio of the average RI value in the frontal leads (FM) and in the occipital leads (OM), in total in the left and right hemispheres. The partial gradient was calculated by the ratio of the RI values in the frontal lead (FM) and in the occipital lead (OM) of the corresponding hemisphere: the right diagonal gradient was calculated by the ratio of Fmd to Oms, and the left diagonal gradient was calculated by the ratio of Fms to Omd. So, if the gradient index was greater than one, this indicated a hyperfrontal gradient, if less than one, then a hyperoccipital one. When equal to one, there was no gradient between the frontal and occipital leads.

Statistical analysis for independent variables was determined by the non-parametric Mann-Whitney method. For dependent variables using the Wilcoxon test using the SPSS program.

Results

Dynamics of changes in the general front-occipital gradient

In the group of subjects in the initial state, the hyperfrontal gradient prevailed (Fig. 1). The fronto-occipital gradient during the GO/NOGO test increased throughout the entire task, indicating an increase in blood supply to the frontal lobes in the subjects. Thus, a statistically significant increase in the fronto-occipital gradient was detected in the first minute of the second part ($p = 0.042$) and in the last minute ($p = 0.04$) of the GO/NOGO test. The obtained data confirm the assumption about the formation of a hyperfrontal gradient during the mental load of the GO/NOGO test, which indicates an increase in the blood supply to the frontal lobes to ensure the most effective control of the behavior of the subjects. Thus, a change in the general fronto-occipital gradient can serve as a functional marker of cerebral circulation restructuring during mental activity.

Dynamics of changes in partial fronto-occipital gradients

When studying the dynamics of particular fronto-occipetal gradients, the greatest increase in the first half of the test was found in the right-diagonal fronto-occipetal gradient (right forehead/left occiput) (Fig. 2). This is confirmed by a statistically significant increase in the gradient at 3 minutes of the test, compared with the initial state ($p = 0.018$). In the literature, based on the results of EEG, this diagonal gradient is called the «axis of superconsciousness» or «creative axis» (Sviderskaya, 2011). In the second half of the trial, an increase in partial gradients was observed for the left diagonal fronto-occipetal gradient (left forehead/right occiput) and fronto-occipetal gradient of the left hemisphere. A statistically significant increase in the left-diagonal gradient relative to the initial state is found already in the first minute of the second part of the test ($p = 0.038$). In the literature, this diagonal gradient has been called the «cognitive axis» (Dzhebrailova & Korobeinikova, 2013; Razumnikova, 2003). Throughout the test, there was an increase in the fronto-occipital gradient in the left hemisphere (left forehead/left occiput), however, a statistically significant increase was found only in the last minute ($p = 0.044$). The least pronounced changes in the fronto-occipital gradient are observed in the right hemisphere. Thus, a detailed study of the dynamics of the fronto-occipital gradient revealed the earliest changes during the mental activity of the right-diagonal gradient. And later growth of the fronto-occipital gradient in the left hemisphere and the left-diagonal gradient.

Correlation: gradients and precision

We made an attempt to evaluate the relationship between changes in the general and particular gradients during the execution of the GO/NOGO test and the number of errors per non-significant rare stimulus (NOGO). Thus, it would be possible to determine the relationship between the efficiency of the task and the features of the spatial reorganization of the cerebral blood flow. However, it was not possible to identify statistically significant patterns.

Correlation: first minute gradient change and accuracy

Next, we made an attempt to evaluate the relationship between reactive changes in the general and particular gradients in the first minute of the trial and the number of errors. For this, the conditional value of the change in the gradient between the first minute of the first part of the GO/NOGO test and the state of readiness, the difference of these values, was calculated. Correlating the number of errors with the calculated conditional value of the gradient change allows us to observe how the reactive gradient change in the first minute affects the accuracy of the GO/NOGO test as a whole.

Correlation analysis of changes in total FOG in the first minute of the 1st part of the task had a weak negative (-0.384) but statistically significant ($p = 0.012$) relationship with the number of NOGO errors. Next, a similar correlation analysis of partial FOGs was performed with the accuracy of the task. A statistically significant ($p = 0.023$) weak negative relationship (-0.355) was found between changes in the right diagonal gradient in the first minute of the GO/NOGO trial and NOGO errors (Fig. 3). The reactive change in the gradient in the left hemisphere, as well as the change in the left diagonal gradient, had only a tendency to a weak negative correlation. No relationship was found between gradient changes in the right hemisphere and task performance accuracy.

Thus, the right-diagonal fronto-occipetal gradient turned out to be most associated with effective control of mental activity. In subjects, the growth of this gradient at the beginning of mental activity correlates with high accuracy in completing the task. In this regard, it is proposed to call the right-diagonal front-occipetal gradient not the «axis of superconsciousness», but the «axis of reactive control».

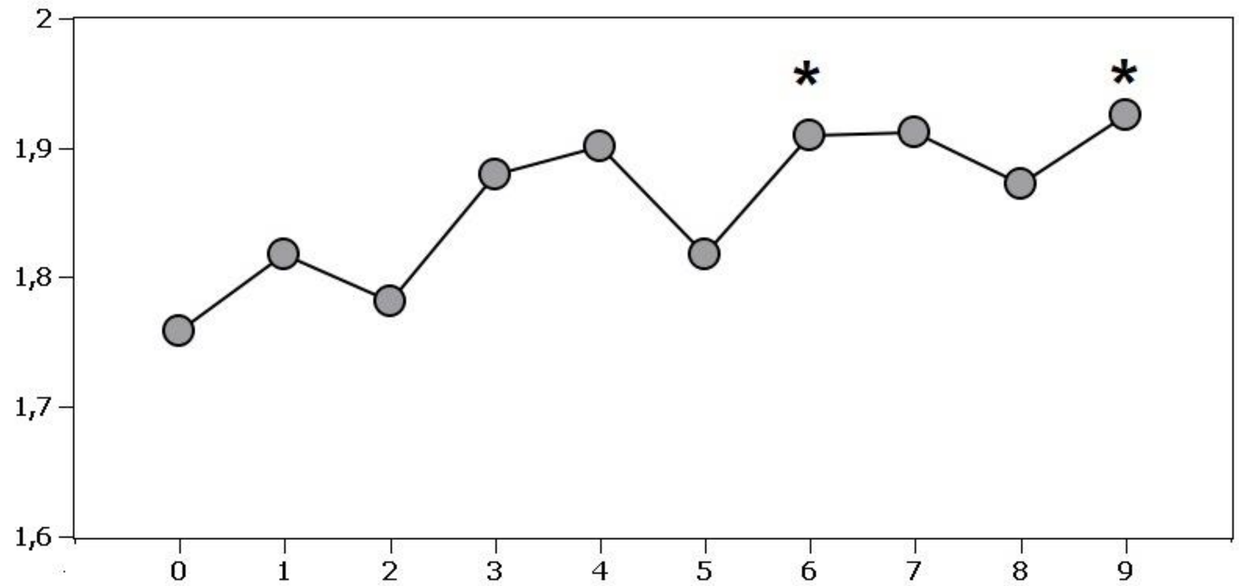

Fig. 1. Dynamics of changes in the fronto-occipital gradient during the GO/NOGO test. On the X-axis: 0 initial level of the fronto-occipital gradient; numbers 1; 2; 3; 6; 7; 8 shows the values of the fronto-occipital gradient at the first, second, and third minutes of the task in the first and second parts, respectively. The number 5 indicates the level of the fronto-occipital gradient during the rest between the 1st and 2nd parts of the task, the numbers 4 and 9 are the values of the fronto-occipital gradient at the last minute in the first and second parts, respectively. On the Y axis, the value of the fronto-occipital gradient. * – statistically significant differences from baseline ($p < 0.05$)

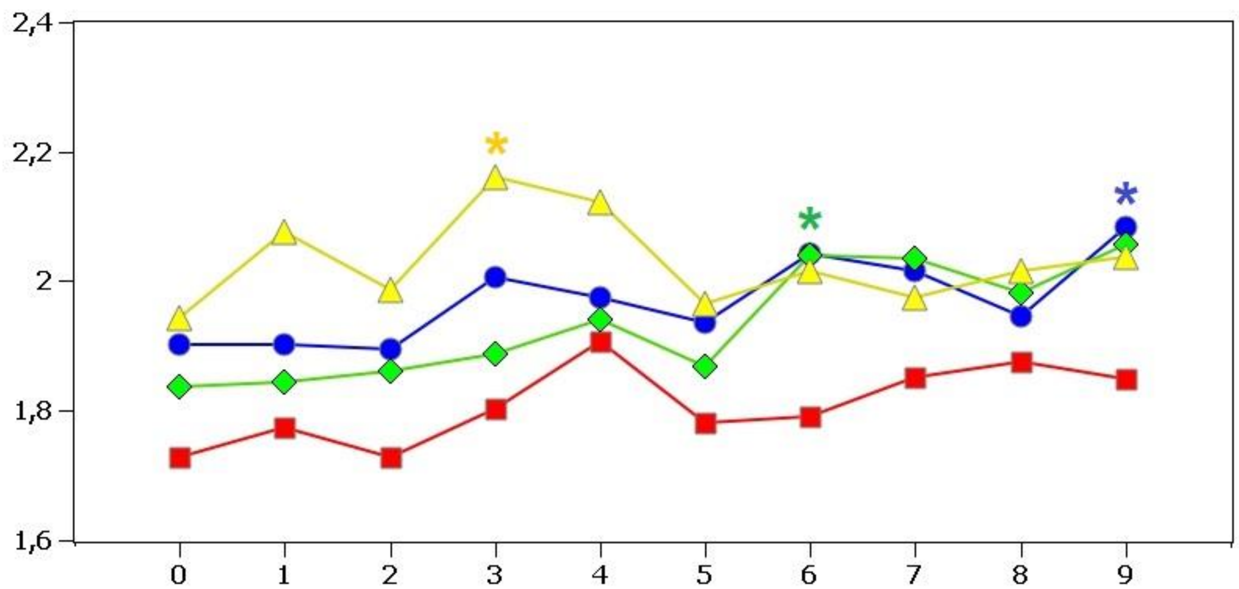

Fig. 2. Dynamics of changes in the fronto-occipital gradient during the execution of the GO/NOGO test. On the X-axis: 0 initial level of the fronto-occipital gradient; numbers 1; 2; 3; 6; 7; 8 shows the values of the fronto-occipital gradient at the first, second, and third minutes of the task in the first and second parts, respectively. The number 5 indicates the level of the fronto-occipital gradient during the rest between the 1st and 2nd parts of the task, the numbers 4 and 9 are the values of the fronto-occipital gradient at the last minute in the first and second parts, respectively. Red squares – fronto-occipital gradient of the right hemisphere. Blue circles fronto-occipital gradient of the left hemisphere. Yellow triangles - right diagonal fronto-occipital gradient (reactive axis). Green diamonds - left diagonal fronto-occipital gradient (cognitive axis). On the Y-axis, the value of the fronto-occipital gradients. * – statistically significant differences from the initial level ($p < 0.05$) corresponding to the color of the gradient

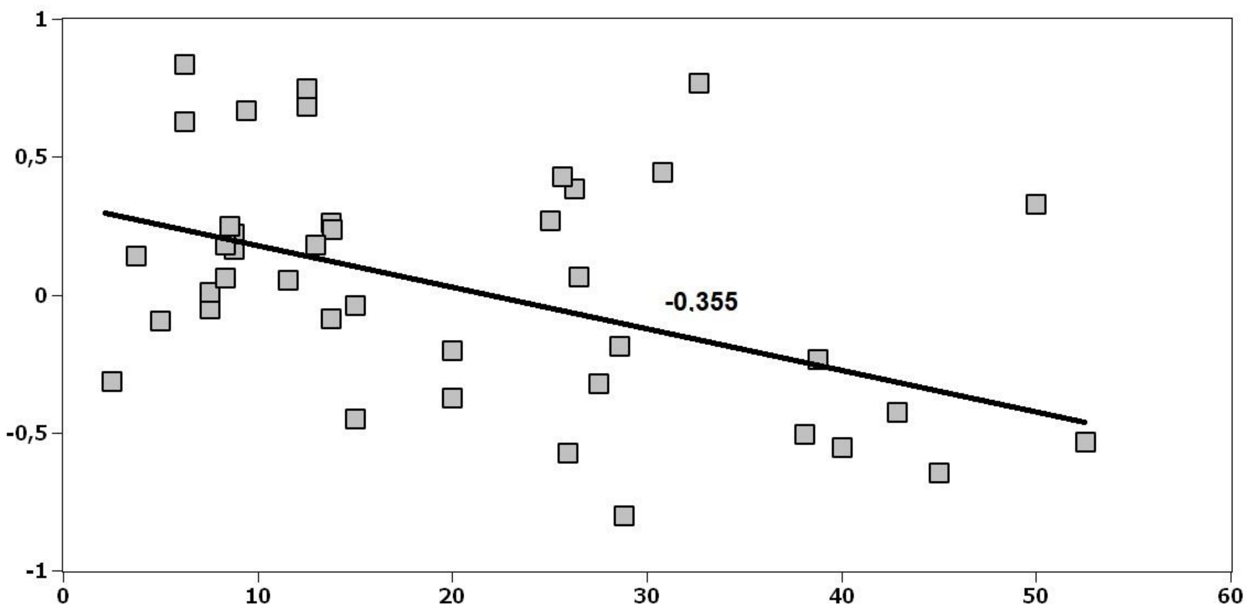

Fig. 3. Scattergram of the correlation analysis of changes in the right diagonal fronto-occipital gradient (reactive control axis) in the first minute of the first part of the GO/NOGO test task (Y axis) and the percentage of NOGO errors (X axis)

Discussion

The data obtained on the increase in total FOG suggest that the redistribution of blood supply in favor of the frontal regions plays an important role in urgent adaptation to mental stress. During active brain maturation during the school period, FOG in children with learning problems (with mental retardation) is lower than in other schoolchildren (Azatyan & Grigoryan, 2018). As the brain matures during the school period, accompanied by mental stress, an increase in FOG is observed. As children progress through the school curriculum, indicators of cognitive activity increase - the complexity of tasks, the growth of indicators of voluntary attention and memory, fluency of speech, etc. (Isaeva *et al.*, 2005). It can be assumed that the development of cognitive activity is associated with the formation of an appropriate spatial organization of cerebral circulation. Other neuroimaging methods show similar data. For example, an increase in the fronto-occipital alpha rhythm gradient as the brain matures in the preschool and school years (Sokolovskaya, 2001; Blagosklonova & Novikova, 1994). As well as the connection between the spatial organization of the EEG and the success of training. In our study, for the first time, an increase in FOG was shown in adult subjects during mental stress. A more difficult task is to describe the features in the dynamics of partial FOGs. The right-diagonal FOG (reactive control axis) turned out to be the fastest and most sensitive to mental stress. When studying spontaneous electrical activity under conditions of excessive information load and requiring imagination, successful subjects showed high EEG coherence between the right frontal and left occipital leads (Dzhebrailova & Korobeinikova, 2013; Sviderskaya, 2011). It is known that the simultaneous nature of information processing is associated with the right hemisphere, and the detection of visual verbal stimuli is carried out by speech centers in the left visual cortex (Zaltsman & Meyerson, 1990; Leushina & Nevskaya, 2004). The first part of the GO/NOGO test is characterized by a lack of experience and a high level of uncertainty, which requires the activity of the frontal regions of the right hemisphere. The use of verbal stimuli presented on a monitor activates the left visual cortex.

In the second part of the task, there is also an increase in partial FOGs of the left hemisphere and the «cognitive axis». These changes in the spatial organization of brain blood filling can be explained by the more successive nature of the task (left hemisphere), as well as in connection with the emergence of experience and its automation (right occipital-parietal region). The absence of pronounced FOG dynamics in the right hemisphere can be explained by the fact that operator activity on a computer is more related to the predominantly successive type of information processing characteristic of the left hemisphere.

In this study, it was not possible to find a relationship between the accuracy of the task and the indicators of general and partial FOG both in the initial state and during mental stress.

In contrast to an earlier study, which showed a relationship between task performance accuracy and bilateral asymmetry in the basins of the internal carotid arteries. The predominance of blood filling in the left internal carotid artery was associated with greater accuracy (Prodius *et al.*, 2023). It can be assumed that the fronto-occipital organization of blood circulation is associated with the switching of global neural networks of the cerebral cortex involved in cognitive activity (Colom *et al.*, 2009; Marek & Dosenbach 2018; Niendam *et al.*, 2012). Switching to the fronto-occipital network of the right hemisphere occurs when performing simultaneous tasks, and to the fronto-occipital network of the left hemisphere when performing successive operations. The neural network associated with the «reactive control axis» is activated to solve an unfamiliar task, and the neural network of the «cognitive axis» is activated when working with more automated and algorithmic activities. The hypothesis about the switching role of FOG is confirmed by the discovery of a relationship between the change in the total FOG in the first minute of the GO/NOGO task and the number of errors during the entire task. Of all private FOGs, a statistically significant correlation was found in the «reactive control axis». Presumably, the restructuring of blood flow along this axis allows the dorsolateral prefrontal cortex to exercise reactive inhibitory control more effectively and make fewer errors.

Thus, FOG is a sensitive functional marker of the spatial organization of cerebral circulation during mental activity. Earlier changes were found for the «axis of reactive control», as one develop into mental activity, there is also an increase in the indicators of FOG of the «cognitive axis» and FOG of the left hemisphere. Promising indicators for predicting the success of mental activity were the nature of reactive changes in the total FOG and the «axis of reactive control» in the first minute of mental load.

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