STUDY OF NEUROPHYSIOLOGICAL AND HEMODYNAMIC INDICATORS IN PERSONS WITH HIGH AND LOW LEVELS OF EXECUTIVE CONTROL

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Abstract. This work is devoted to the study of the individual characteristics of cerebral circulation, galvanic skin response and heart rate during mental, sensorimotor and sensory activity. In two groups, differing in the level of behavior control (precise and imprecise), a comparative analysis of behavioral and physiological indicators was carried out. Imprecise subjects before the test (readiness state) GO/NOGO showed higher indices of the tone of the arterioles and venules of the cerebral vessels in the basin of the carotid arteries. During the GO/NOGO trial, a more reactive increase in vascular tone was observed in the precise group, more pronounced in the right hemisphere. In the imprecise group, a higher level of mental stress was registered in terms of GSR and heart rate during mental counting. GSR was also more pronounced in this group when viewing images. The optimal and non-optimal types of information load portability are discussed.

Keywords: mental activity, information loads, behavior control, typology of mental activity, GO/NOGO test, rheoencephalography, galvanic skin response, information stress.

List of abbreviations

Reo – Rheoencephalography
GSR – Galvanic skin reaction
RI – rheographic index
Aart – Amplitude of the anacrotic wave
Aven – Venous component wave amplitude
Aints – Amplitude of the incisura
Adik – Diastolic wave amplitude
FM – Fronto-mastoid abduction
OM – Occipito-mastoidal abduction
ESS – Emotionally significant stimulus
EIS – Emotionally insignificant stimulus

Introduction

Over the past 30–40 years, the information component has become significantly more complex. Therefore, one of the topical trends in physiology is the study of the mechanisms of mental activity under conditions of information stress. Informational loads should be considered systemically, that is, as a factor that causes both mental stress and a deviation of homeostatic indicators. Among the behavioral indicators of mental activity, one can distinguish reaction time, variability in response time, and the number of errors. Low portability of information loads is primarily characterized by an increase in the number of errors. The more difficult the task, the longer the reaction time and the greater the percentage of erroneous answers. Low resistance to mental stress is associated with low maturity of the frontal cortex, impaired cerebral circulation, imbalance in the processes of excitation and inhibition, organic disorders of the cerebral cortex and subcortical structures.

At the same time, mental activity is accompanied by a certain emotional background. With an increase in the difficulty of the task, emotional stress increases, which can be registered by an increase in skin electrical conductivity (galvanic skin response, GSR). Addiction, on the contrary, reduces the amplitude of GSR. Emotional stress is associated with the activity of the subcortical structures, which are commonly called the limbic system. The severity of GSR is associated with an increase in the tone of the sympathetic nervous system and an increase in a person's mental stress.

These structures are involved in the so-called unconscious or poorly understood information processing processes. Individuals with low emotional stability are more susceptible to increased mental stress and mood instability (Grab et al., 2010).

Thus, the mental activity of a person and the severity of mental stress can be associated with the ratio of the activity of cortical and subcortical structures.

Any mental stress is associated with a pronounced deviation of homeostatic indicators, which is commonly called physiological stress. First of all, the working hyperemia of functionally active tissue requires a more active inflow and outflow of blood. Consequently, the total blood flow by central mechanisms will be redistributed in favor of metabolically active tissues. Therefore, it is advisable to study the influence of information load on physiological indicators by the indicators of cerebral circulation. For example, using indicators of pulse blood filling, recorded using rheoencephalography. According to the literature, during mental exertion, there is an increase in the rheographic index (RI) and the amplitude of the maximum systolic value of the venous component (Aven) (Azatyan & Grigoryan, 2018). As the brain matures, schoolchildren show significant changes in the level of blood flow and an increase in the proportion of blood flow in the frontal region. To date, the formation of a gradient of blood filling between the frontal and mastoid basins of the brain in children aged 8–11 is normal (Zhivotova & Voronova, 2010).

The aim of the work was to compare the indicators of mental stress and hemodynamic differences in the frontal regions between the two groups differing in the number of errors in the GO / NOGO test.

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. To divide into groups with low and high executive control, the subjects were asked to perform a task for control of attention, consisting of two parts, 7.5 minutes each with a short break between them. When presented with stimulus material in the form of frequent significant (GO – letter H), insignificant rare (NOGO – letter I) and insignificant rare (Novel – various signs @,?, #, Etc.), subjects pressed certain buttons (Gomez et al., 2007). The stimulus material was presented on the monitor using the PsychoPy program (Peirce, 2009). According to the results of the implementation of the protocols, the subjects were divided into 2 groups: «precise» (error < 15%) and «imprecise» (error > 15%). At the same time, a rheoencephalogram was recorded using the Rheo-Spectrum rheoencephalograph (Neurosoft, 2008) with the determination of the following parameters: the amplitude of the arterial component of the wave (Aart), the amplitude of the maximum systolic value of the venous component (Aven), the amplitude of the wave at the incisure level (Aints), the amplitude at the level of the diastolic wave, indicating the state of the outflow of blood from the arteries to the veins and the tone of the veins (Adik). To study the total blood supply of the cerebral hemispheres, the frontal-mastoidal (FM) and occipito-mastoidal (OM) leads are used. Using a computerized polygraph KARDi2-NP, simultaneously with the presentation of stimuli, the galvanic skin response were recorded during tests with passive perception and «mental counting» (Sukhoedov, 2007). Statistical analysis for the explanatory variables was determined by the nonparametric Mann-Whitney method. For dependent variables using the Wilcoxon test using the SPSS program.

Results

Cerebral circulation in a state of readiness

The first minute of the rheogram was recorded at the moment when the subjects had already been instructed on the principles of the experiment and the conditions for performing the task. Thus, the Aart indicator tended to increase in the group of «imprecise» in the readiness state in the right hemisphere (p = 0.108) (Fig. 2). The Aven index was higher in the «im-

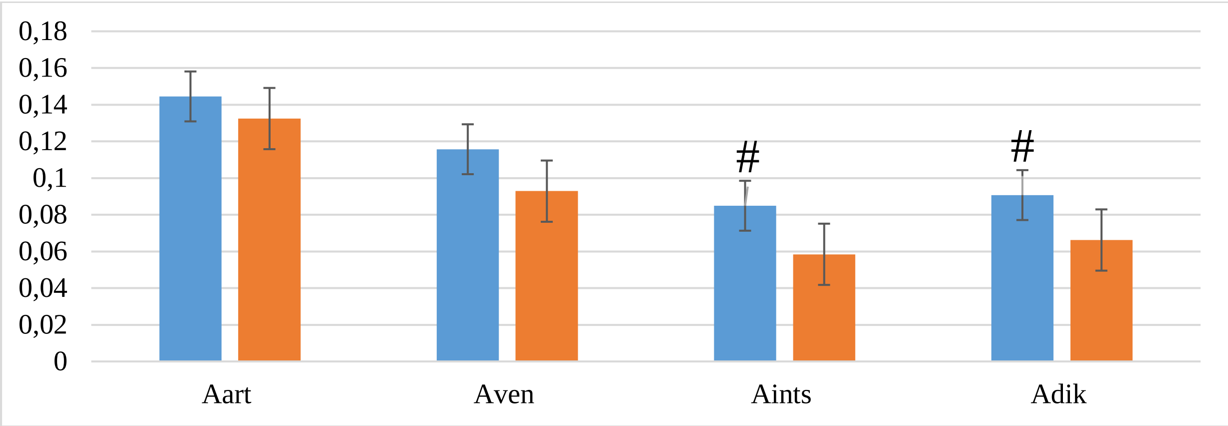

Fig. 1. Comparison of indicators of blood flow in a state of readiness between the groups "precise» and «imprecise», the left hemisphere. On the X-axis, the rheoencephalogram indicators (Aart, Aven, Aints Adik), on the Y-axis, the average amplitude of the indicators in Ohms. Blue for imprecise, brown for precise. # – $p < 0.1$

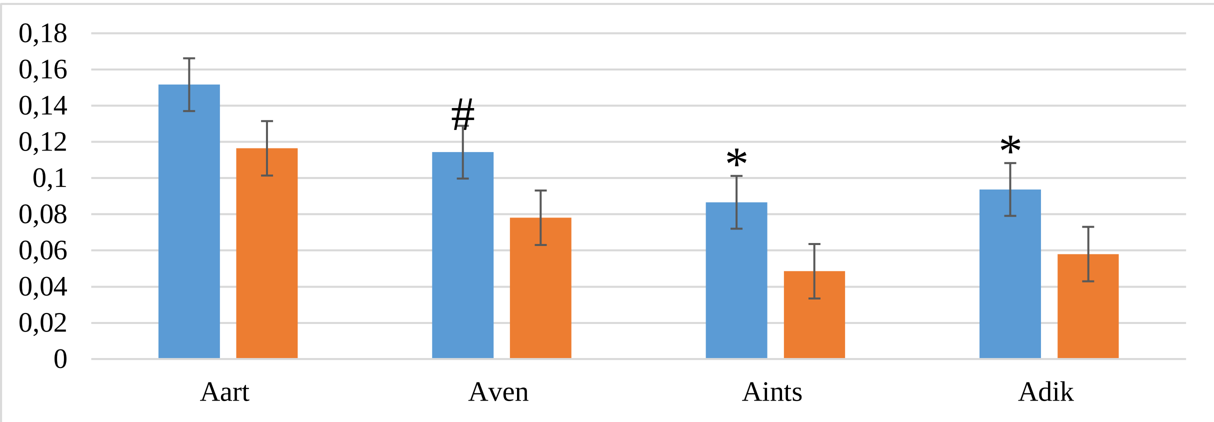

Fig. 2. Comparison of indicators of blood flow in a state of readiness between the groups «precise» and «imprecise», the right hemisphere. On the X-axis, the rheoencephalogram indicators (Aart, Aven, Aints Adik), on the Y-axis, the average amplitude of the indicators in Ohms. Blue for imprecise, brown for precise. * – $p < 0.05$; # – $p < 0.1$

precise» group both in the left (p = 0.108) (Fig. 1) and in the right hemisphere (p = 0.096). The Ainz index was significantly higher in the «imprecise» group in the left (p = 0.056) and right (p = 0.036) hemispheres. The Adik value was also higher in the «imprecise» group both in the left (p = 0.096) and significantly higher in the right hemisphere (p = 0.042).

Cerebral hemodynamics depending on the effectiveness of the task «GO/NOGO»

Analysis of the absolute averaged values in the «precise» and «imprecise» groups revealed a number of differences. Thus, the amplitude of the arterial component of the wave (Aart) was statistically significantly higher (p = 0.037) (Fig. 3) in the «imprecise» group on the second minute of the first half of the protocol in the left hemisphere. In the right hemisphere, this indicator was higher in the «imprecise» group in the second minute of the first half of the protocol (p = 0.032) and in the last minute of the second half of the protocol (p = 0.032) (Fig. 3). In general, this indicator allows one to judge about a greater blood supply to the frontal areas in the «imprecise» group than in the «accurate» group.

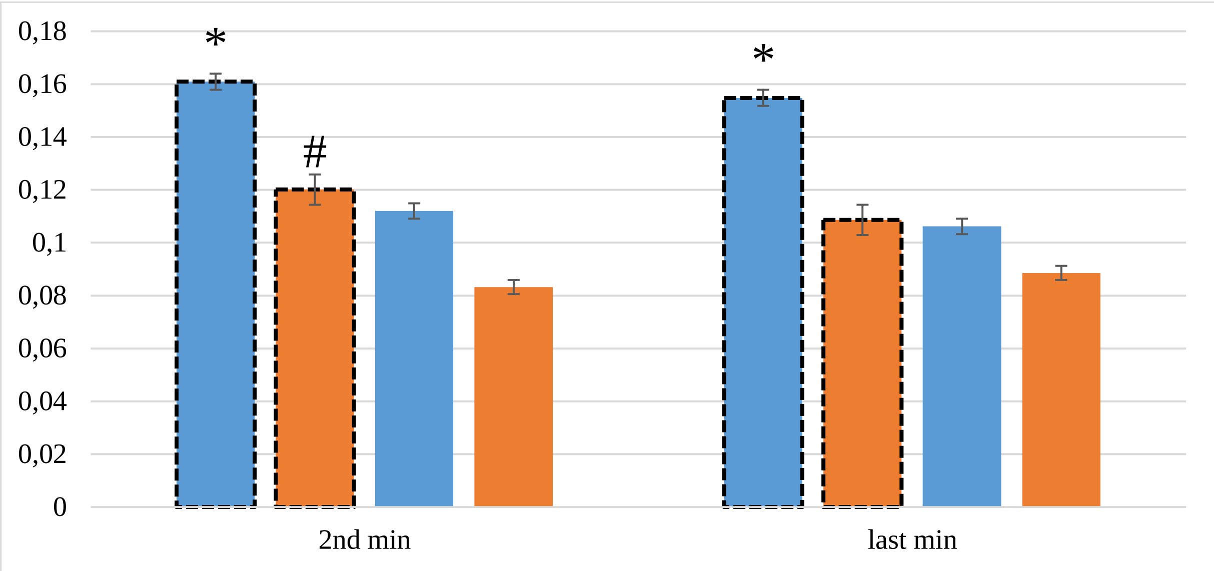

Fig. 3. Comparison of amplitudes of Aart and Aven in the groups «precise» and «imprecise» in the right hemisphere during the test GO/NOGO. On the X-axis, the test run time (2nd min and last min), on the Y-axis, the average amplitude of the indicators in Ohms. Blue for Aart, brown for Aven, black outline for imprecise, without outline for precise. * – p <0.05; # – p < 0.1

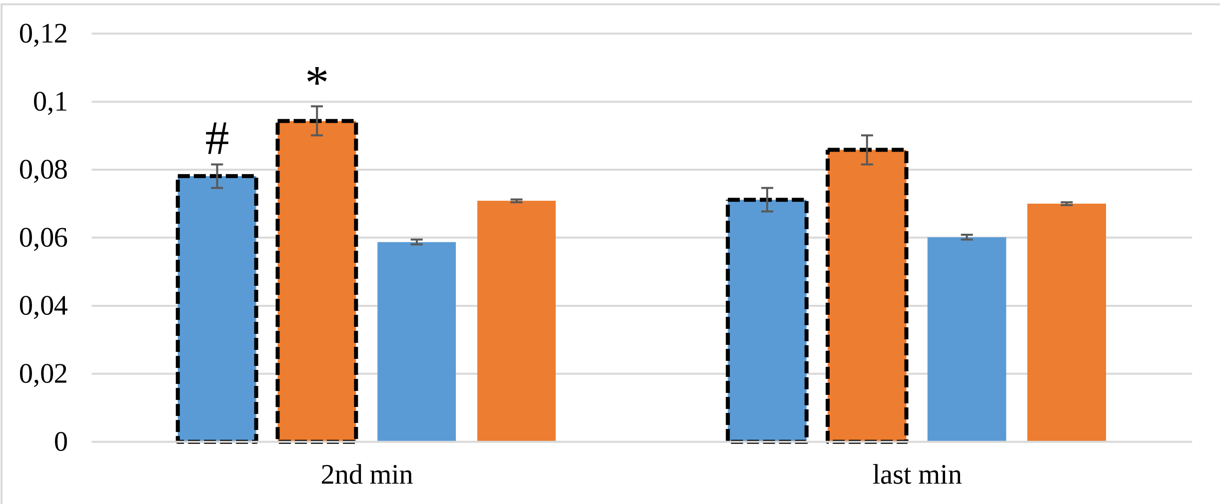

Fig. 4. Amplitudes Aints and Adik in the groups «precise» and «imprecise» in the right hemisphere. On the X-axis, the test run time (2nd min and last min), on the Y-axis, the average amplitude of the indicators in Ohms. Blue for Aints, brown for Adic, black outline for imprecise, without outline for precise. * – p < 0.05; # – p <0.1

The Aven index characterizing peripheral vascular resistance was tendentiously higher in the «imprecise» group in the left hemisphere in the second minute of the first half of the protocol (p = 0.051) (Fig. 3), as well as in the second minute in the first half of the protocol in the right hemisphere (p = = 0.091) (Fig. 3).

Aints score was higher in the «imprecise» group in the right hemisphere in the second minute of the first half of the task (p = 0.051). On the second minute of the first half of the protocol in the right hemisphere, Adik was significantly higher in the «imprecise» group (p = = 0.037) (Fig. 4). There were no differences in the left hemisphere.

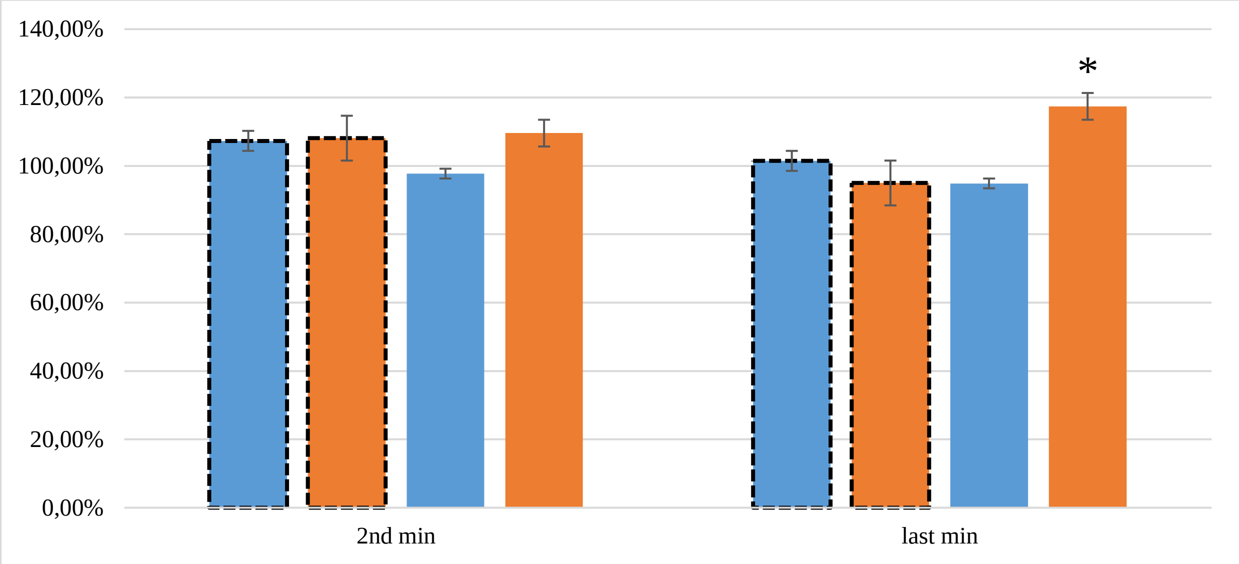

Fig. 5. Changes of the amplitudes in cerebral hemodynamics in the groups «precise» and «imprecise» in the right hemisphere (Aart, Aven). On the X-axis, the test run time (2nd min and last min), on the Y-axis, the percentage change relative to the state of readiness. Blue for Aart, brown for Aven, black outline for imprecise, without outline for precise. * – $p < 0.05$

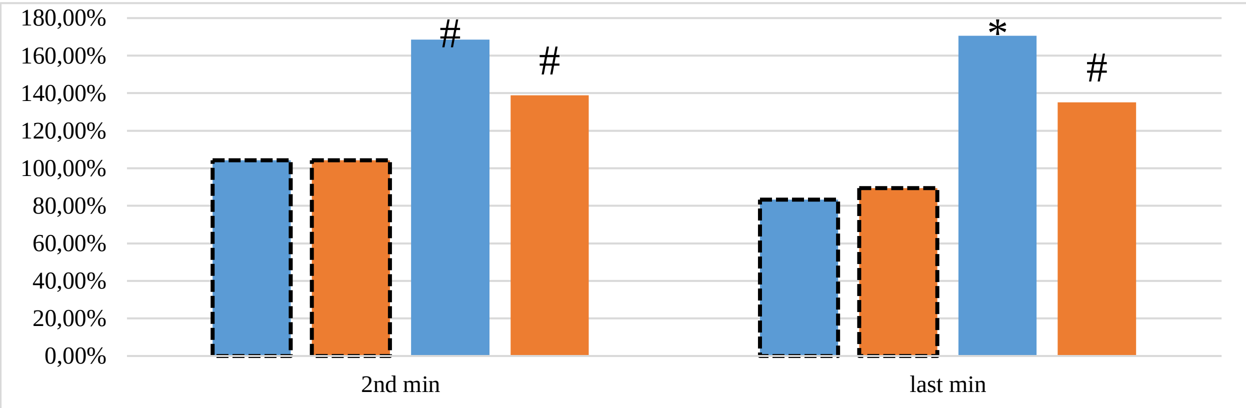

Fig. 6. Changes of amplitudes in cerebral hemodynamics in the groups «precise» and «imprecise» in the right hemisphere (Aints, Adik). On the X-axis, the test run time (2nd min and last min), on the Y-axis, the percentage change relative to the state of readiness. Blue for Aints, brown for Adik, black outline for imprecise, without outline for precise. * – $p < 0.05$; # – $p < 0.1$

Further, the assessment of changes in cerebral hemodynamics in percent was made. The readiness state recorded immediately before the test was taken as one hundred percent. The nature of hemodynamic changes during the task between the groups was very different.

In the dynamics of changes in blood circulation at the Aart level, there were no significant differences between the groups of «precise» and «imprecise». The change in the Aven score was significantly higher in the «precise» group at the last minute of the protocol in the right hemisphere ($p = 0.032$) (Fig. 5).

Aints's change in the right hemisphere was more reactive. Thus, in the «precise» group, a significant increase in this indicator was observed in the second minute of the first half of the protocol ($p = 0.051$) and in the last minute of the protocol execution in the right hemisphere ($p = 0.027$) (Fig. 6).

Changes in the Adik indicator were also characterized by its growth in the «precise»

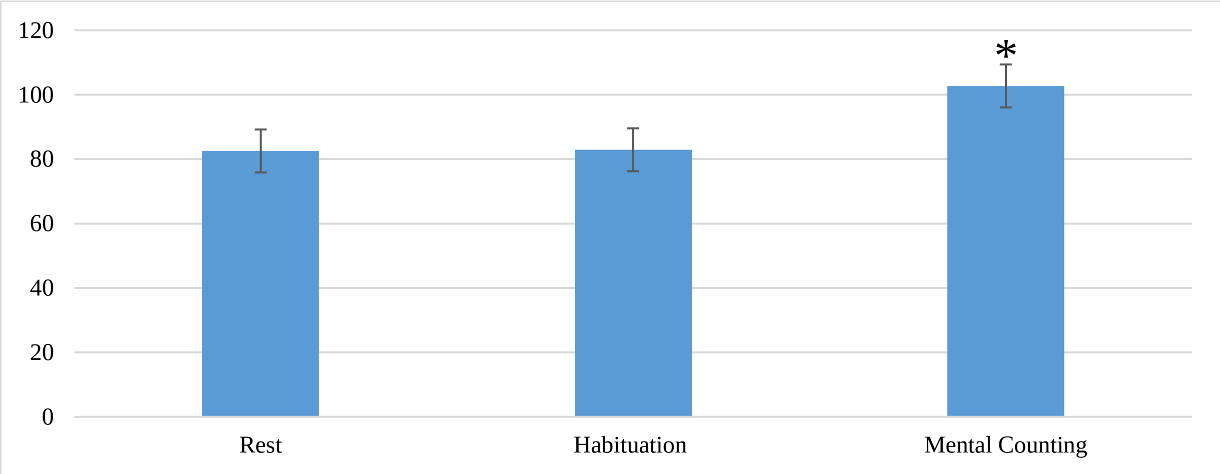

Fig. 7. Dynamics of changes in heart rate of all subjects in different tests. On the X-axis, the samples (rest, habituation test, «mental counting» test), on the Y-axis, the heart rate in bpm. * – $p < 0.05$ compared to rest

group, mainly in the right hemisphere, at the second and last minute of the protocol (p = = 0.059; p = 0.069).

Comparison of heart rate in two samples

When comparing the heart rate in tests for habitation and counting with the pre-start state before the habituation test, taken as rest, a statistically significant difference was revealed between the test «mental counting» and the resting state (p = 0.0001) (Fig. 7).

In the habituation test, an increase in heart

rate was observed in the «imprecise» group, while in the «precise» group, the heart rate decreased as the test progressed. When analyzing the heart rate in the «mind counting» test, an increase in this indicator was observed in both groups relative to the pre-start state, with a maximum in the middle of the test. At the same time, the heart rate in the «imprecise» group was higher than in the «precise» group.

Analysis of galvanic skin reactions of two different groups during tests with different levels of voluntary control

The mean values of the GSR amplitude of the two groups were used. The analysis was carried out in the whole trial and by groups of stimuli.

Habituation test

The analysis of the GSR amplitude was carried out in relation to the reaction at rest, taken as 100%. In the «precise» group, the response to the first emotionally significant stimulus was higher than in the «imprecise» group by 14.5%. In this case, the further reaction in the «precise» group decreases, starting from the second presentation, and remains approximately at the same level. In the «imprecise» group, the response to the second presentation relative to the first decreases insignificantly and slightly increases with further presentation of the stimulus. However, there were no statistically significant differences. When comparing the mean values of the GSR amplitude, a tendency to higher values in the «imprecise» group (p = = 0.189) was revealed than in the «precise» group. In the subjects of the «precise» group, after viewing emotionally insignificant images, the stress increased again for an emotionally significant stimulus.

«Mental counting» test

We analyzed the data obtained at the moment of direct counting in the minds of the subjects and after they voiced the result of the calculations. The data were compared between the two groups and within each of the groups.

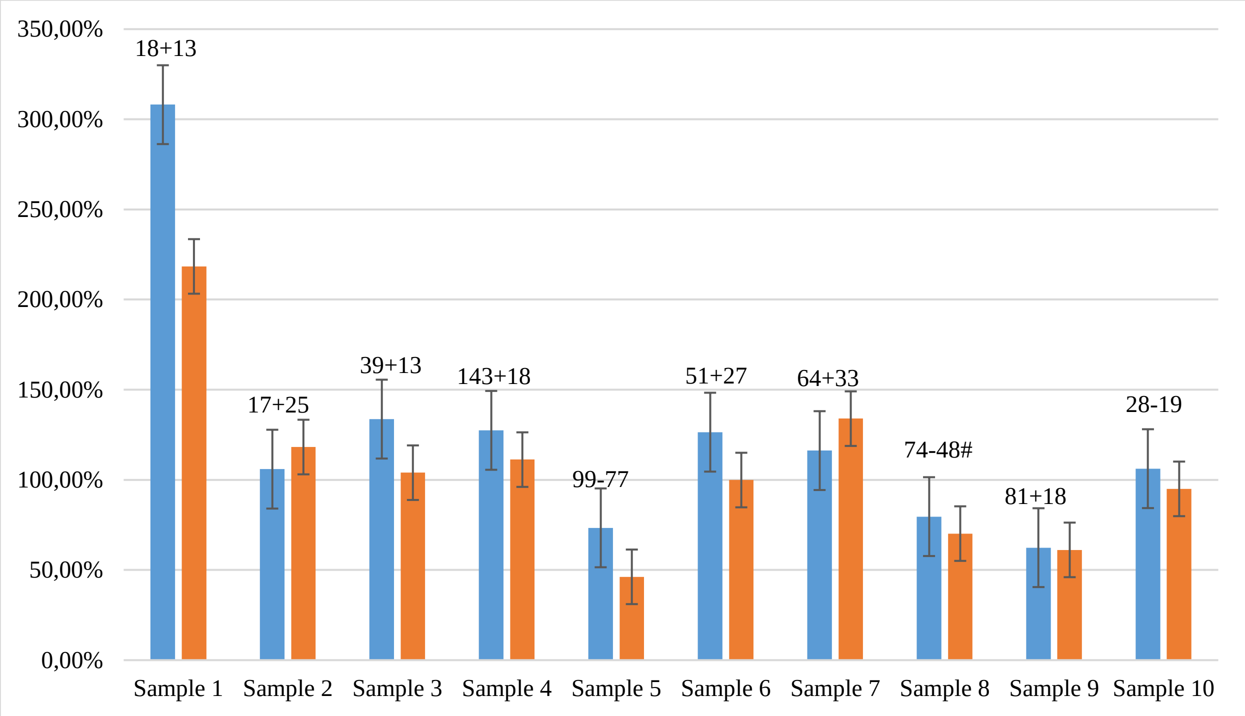

Fig. 8. Comparison of the changes of GSR amplitude, on mental counting, of subjects in the «precise» and «imprecise» groups in the «mental counting» test. On the X-axis, the samples of «mental counting» test, on the Y-axis, the percentage change relative to the state of readiness. Blue for imprecise, brown for precise. # – $p < 0.2$

When analyzing the mental counting of the subjects, it was found that the stress in the «imprecise» group for almost all mathematical stimuli was higher than in the «precise» group. So, when performing example No. 8 (74-48), a tendentious difference was found p = 0.135 (Fig. 8). At the same time, for the first example in the «imprecise» group, the orienting response was higher than in the «precise» group.

When analyzing the data obtained after the respondents' answer, it was found that in the «precise» group the voltage was much higher than in the «imprecise» group. A statistically significant difference was found after the given answer when solving example No. 8 ($p = 0.018$). Tendentious differences were revealed after the data answers when solving examples No. 2,3,6,7 – $p = 0.145$; $p = 0.190$; $p = 0.135$; p = 0.073, respectively. A tendentious difference was also revealed when analyzing the mean values of the response after the response was voiced ($p = 0.135$).

Discussion

The result of completing the task may directly depend on how precisely before the beginning of the task, the subjects will be ready for mental stress. The principle of restructuring the cerebral blood supply before starting to perform a particular task, implying mental stress or executive control, may be key in understanding the influence of cerebral hemodynamics on the efficiency of task performance. The data obtained indicate that, in general, the tone of the cerebral vessels in the «imprecise» group is initially higher than in the «accurate» group. This may indicate the obstruction of blood flow in the frontal lobes and, as a consequence, the low efficiency of their work. There is information in the literature indicating the importance of a drop in the tone of the cerebral arteries as a means of increasing blood supply for adequate maturation of the frontal lobes in children (Azatyan & Grigoryan, 2018).

In addition, the index of cerebral vascular blood filling (Aart) in the left and right hemispheres is higher in the «imprecise» group, which means a greater blood supply to the brain in general, in «imprecise» subjects than in «accurate» subjects. Such results may indicate an ineffective and uneconomical expenditure of resources in the «imprecise» brain. Lower indices of blood supply to the brain in the «accurate» group may be associated with adaptation to mental stress and focal distribution of blood flow, versus generalized in «imprecise» ones.

When assessing the absolute averaged values, the vascular tone and blood supply were higher in the «imprecise» group. However, when assessing the dynamics of changes in vascular tone during the protocol, the greatest changes were observed in the «precise» group. First of all, it can be judged that the brain of «accurate» subjects responds more reactively to cognitive load and self-control, which causes significant changes in the hemodynamics of its frontal lobes. While the brains of the «imprecise» subjects initially had a higher vascular tone and a higher, generalized blood supply, which could limit the range of adaptive capabilities. So, when performing the task, in the changes in the cerebral hemodynamics of the «imprecise» subjects, no significant rearrangements in the regulation of blood flow were noticed.

The data obtained, in addition, allow us to note that the cerebral hemodynamics of the «precise» subjects, first of all, significantly differed in the Aints and Adik indices in the right hemisphere both at the beginning and at the end of the task. An increase in venous tone and peripheral vascular resistance during mental stress may indicate a redistribution of blood in the brain, in order to provide not generalized blood supply to all frontal regions, but to concentrate blood flow in the most active areas, for greater efficiency of task performance and self-control. The changes in Aints and Adik for the left hemisphere were qualitatively similar for the groups. But in the group of imprecise subjects, the fall of Aints and Adik was not observed at the end of the second part of the task, as was observed in the right hemisphere. The data obtained show the presence of individual differences in the tone of arterioles and venules during mental exercise in the right hemisphere.

Previously, it was believed that the severity of the role of autoregulation of cerebral blood flow fully compensates for the indicators during mental stress. When comparing the normalized indices confined to the data of rheoencephalography at rest, it can be said that the indices of the left frontal region remain more compensated during the information load. In the right frontal region, more reactive changes in blood flow are observed, which in some of the subjects cannot adapt (stabilize) by the end of the task. These deviations in the form of a decrease in vascular tone indicators, impaired blood flow and venous outflow can be interpreted as physiological stress. According to literature data, using near infrared topography and spectroscopy, a decrease in blood flow in the right frontal region in persons with attention deficit hyperactivity disorder in the go / know go test and the Stroop test was shown. Recovery of executive function after treatment is accompanied by an increase in blood flow in the right frontal region (Moser *et al*., 2009; Monden *et al*., 2012).

The rhythm of heart contractions is the most accessible physiological parameter for registration, reflecting the processes of autonomic regulation in the cardiovascular system and the body as a whole. The dynamic characteristics of the heart rate make it possible to assess the severity of shifts in the sympathetic and parasympathetic activity of the ANS when the patient's condition changes (Usanov et al., 2009). We can say that in both groups, the heart rate increases in the «mental count» test, which indicates an increase in the complexity of the tests. The simplest is the habituation test, since the passage of this test does not require the active participation of the subjects and is aimed at passive perception of stimuli. The most difficult test turned out to be the «mental counting» test, as it requires the participation of working memory and behavior control.

It is believed that the habituation reaction occurs after an orienting reaction after about 5-10 repetitions of the same emotionally significant stimulus (Nebylitsyn, 1990).

Analysis of all samples according to GSR data showed that the greatest mental stress is observed in the «imprecise» group with passive perception of images and performing arithmetic operations.

As is known from literary sources, the cerebral cortex, due to descending influences, can enhance or weaken the manifestations of emotional reactions that have developed at the subcortical level (Aleinikova, 2002). These results suggest that the «precise» test groups have a typical type of response to a stimulus of pronounced emotional significance. While in the «imprecise» group, the reaction is atypical, with a tendency to increase reactivity. It can be assumed that the test groups «imprecise» are more reactive than «accurate» to stimuli, regardless of emotional valence.

For the subjects of the «precise» group, the tension, first of all, increased when the answer was voiced, and the mental load did not cause such a reaction. This may indicate a high degree of self-control in the «precise» group.

In the «imprecise» group, in all tests, except for the time after the arithmetic responses were voiced, a more pronounced GSR level was revealed during passive perception of images, verbal stimuli and during mental activity associated with counting. Such a reaction may be due to insufficient influence of cortical structures or increased influence of subcortical structures. In the subjects of the «precise» group, a more pronounced GSR is observed when recognizing previously presented words and at the moment of sounding the answer of arithmetic examples. Which indicates the greater involvement of these subjects in the process of passing the experiment.

Presumably low executive control of the behavior of the subjects of the «imprecise» group is associated with the subcortical and subcortical-cortical type of higher nervous activity, which is due to the greater involvement of the limbic system and reactive zones of the cerebral hemispheres in behavior. That gives a more impulsive nature of the perception and processing of information. In the subjects of the group «precise» mental activity is associated with the predominance of the cortical and cortical-subcortical type of VNI, with a greater involvement of the frontal cortex. In this regard, it can be assumed that the predominance of subcortical structures over cortical structures causes greater mental stress during information loads.

The data obtained make it possible to distinguish two types of information load execution that require arbitrary control. The first, optimal type of information load portability. At a conscious level, it is associated with the admission of a minimum number of errors when executing instructions. At an unconscious or minimally conscious level, it is accompanied by a less pronounced activation of subcortical structures and a smaller increase in mental stress. At the metabolic level, it is associated with greater reactivity and stability of the mechanisms of regulation of vascular tone in the basin of the right carotid artery. In other words, depending on the task, motivation, task difficulty and typological characteristics of a person, we can observe a conditionally cortical-subcortical type with a low level of errors and a low level of mental stress and stable blood circulation in the frontal cortex.

The second type can be called suboptimal or subcortical-cortical. Suboptimal tolerance of information loads is characterized by a large number of errors, higher mental stress and unstable (deficient) blood circulation in the basin of the right carotid artery.

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