Environment and Social Psychology (2025) Volume 10 Issue 10
doi: 10.59429/esp.v10i10.4165

ISSN: 2424-8975 (O)
2424-7979 (P)

Research Article

Dynamics of spectral characteristics of EEG under induced stress of psychosocial genesis

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ABSTRACT

The purpose of this work was to study the spectral characteristics of the EEG during induced stress of psychosocial origin in young people studying at a higher educational institution.

In 40 subjects (19 men and 21 women), the indicators of the full power of the spectrum (μV^2) in the given frequency ranges, the integral EEG alpha/theta indices for the power of the spectrum were studied using 16 standard leads, and the averaged indicators of the full power of the spectrum (μV^2) in the frontal areas of the left (Fp1, F3, F7) and right (Fp2, F4, F8) hemispheres.

According to the full spectrum power indicator, averaged over 16 active leads, an increase was noted in the Δ-, θ-, α- and β-ranges in the preparatory, reactive and cognitive stages of the stress reaction, which indicated the involvement of all oscillatory systems in the implementation of the stress response, regardless of their relationship with the brainstem, limbic (Δ- and θ-rhythms) or thalamocortical (α- and β-rhythms) structures. The alpha/theta index decreased according to the stages of the Trier test. Psychosocial reactivity in the slow-wave components (Δ- and θ-rhythms) of the power spectrum was more pronounced in men, while in the fast-wave components (β1- and β2-rhythms) - in women. No frontal asymmetry of the alpha rhythm was detected during the experiment.

Keywords: EEG; full spectrum power; alpha/theta; alpha frontal asymmetry; Trier test; psychosocial stress

1. Introduction

The use of the EEG method to search for neurophysiological correlates of discrete psychoemotional states is quite common[1-3]. A separate area of such research is the search for biomarkers of stress reactions and human states based on the characteristics of the electrical activity of the brain[4, 12, 17].

When analyzing this problem, a certain complexity is caused by differences in approaches to the electroencephalographic study of stress. Thus, a number of researchers use the characteristics of the bioelectrical activity of the brain to describe the functional features of the central nervous system of subjects in prolonged (from an hour or more) states of stress or under the influence of prolonged unfavorable factors [13,21, 45], with the emphasis, as a rule, on examining the background EEG recording with closed eyes. In the design of such experiments, the stress state is initially determined using a set of psychological tests or an

ARTICLE INFO
Received: 1 October 2025 | Accepted: 20 October 2025 | Available online: 30 October 2025

CITATION
Sergey TN, Michael SR, Andrey EV. Dynamics of spectral characteristics of EEG under induced stress of psychosocial genesis. *Environment and Social Psychology* 2025; 10(10): 4165. doi:10.59429/esp.v10i10.4165

established medical diagnosis.

Of greater interest are works on neurophysiological studies of short-term induced stress of psychosocial genesis. Acute social stress accounts for a significant share of the various forms of stress affecting the average individual, and also has numerous negative consequences on the functional state and health of a person[9]. EEG studies of acute induced stress are most often carried out with open eyes and active participation of subjects in the experiment, which is accompanied by high motivational arousal, concentration of attention and cognitive loads[25, 41]. Of the wide range of social stressors, only a few are actively used in research: social rejection and social evaluation[33,49]. The Trier social stress test was developed by Kirschbaum et al. in 1993[26]. In general, it includes 5 stages, of which only 3 are stress-inducing. The first is the stage aimed at recording the necessary parameters in a state when the stimulus has not yet acted (background state). Thanks to it, it is possible to record the initiation of a stress reaction in subsequent stages. They - stages 2, 3 and 4 are the periods of time when stress is induced, and in several ways: in the second stage, the subject is asked to write a summary - this is a proactive stage, in which the patient is able to predict a future meeting with an irritant. At the next stage (reactive stage), the patient must speak in front of a "public speaking panel" (a selected group of people who behave neutrally towards the speaker; can be replaced by video filming). During stage 4 (reactive stage), the subject must do mental arithmetic, the accuracy of which is assessed. After the stress-inducing stages, there must be a recovery period (stage 5), during which the researcher has the opportunity to observe the inhibition of stress reactions. In modern studies, there are certain changes in the methodology, which makes it quite labile in use. The Trier test has two immediate stress factors that cause the greatest release of cortisol: uncontrollability, which is manifested in the fact that the subject is not informed in advance about his tasks; and social assessment, which is implemented at stages 3 and 4. Given the duration of the entire experiment, the researcher has the opportunity to observe the initiation of stress (stages 2-3), its full development (stages 3 and 4) and inhibition (stage 5), which allows for its full study. Another positive aspect is the technical possibility of using various methods for recording bioparameters: EEG, ECG, blood sampling at different stages, saliva sampling (to determine the concentration of cortisol), measuring blood pressure and heart rate. All this makes the Trier test a very attractive and informative method for searching for biomarkers of acute stress. When studying induced stress and conducting electroencephalographic studies, spectral analysis methods of EEG are very often used. In most studies, the authors use the dynamics of three groups of characteristics as markers of acute stress: indicators of the total (sum) power of the spectrum in individual frequency ranges (Δ-, θ-, α-, β- and γ-rhythms)[10.18,40]; the ratio of spectral characteristics by frequency components[1,16, 38]; frontal asymmetry of the alpha rhythm[23].

Despite the fact that the current volume of studies using spectral measurements of the EEG to determine neural processes associated with social stress effects is significant, there is no general systemic picture of the neurophysiological correlates of acute psychosocial stress.

The purpose of this work was to study the dynamics of the spectral characteristics of the EEG during induced stress of psychosocial genesis in young people studying in higher education institution.

2. Materials and methods

The use of EEG spectral characteristics to describe adverse effects and stress reactions of various origins is quite common in research practice[3,31,34], but it is less common in relation to the description of induced stress of psychosocial origin[2, 10], although there are some fairly early works[44].

A single (cross-sectional) study involved 40 people (19 men and 21 women), full-time students of Tyumen State University, permanently residing in the Tyumen region, with an average age of 22.4+1.4 years.

The students signed voluntary informed consent to participate in the experiment. The study was approved by the Biomedical Ethics Committee of Tyumen State University. The inclusion criteria were health group 1 or 2, good academic performance at the university (no academic debt, average grade point average of current academic performance >4.0; academic success as a criterion for the effectiveness of the main type of activity); the exclusion criteria were a history of neurological diseases and/or exacerbation of any nosologies in the last two weeks before the study. The work was carried out in the intersession period in the first half of the day in a calm, comfortable environment. The study of induced stress was carried out using a modified version of the Trier Social Stress Test (TSST). The subjects were motivated to obtain high test results. The students were informed that the effectiveness of passing the TSST would be taken into account when choosing a department and a supervisor. At the first stage, EEG was recorded with open eyes in a calm state (control). At the second stage, the subject was asked to prepare (think about) a short resume about himself for his “dream job”. At this stage, the subject could write down his thoughts in a notebook without making any active movements. At the third stage, the subject had to give a self-presentation “on camera”, also avoiding any physical activity. At the fourth stage, the participants in the study counted down out loud, successively subtracting the number 13 from the number 1022. The fifth stage involved calm wakefulness with the eyes open. Each of the five stages lasted 5 minutes, during which the EEG was recorded. The total duration of the experiment, excluding the introductory briefing, was 25 minutes. There were no breaks between the stages of the Trier test.

EEG recordings were conducted with eyes open during all stages of the Trier test, as in real life, psychosocial stressors affect young people under typical behavioral and cognitive load conditions (lectures, presentations at seminars and conferences, report presentations, etc.). All these activities occur with eyes open, and we were interested in observing the brain's bioelectrical activity in this state.

EEG was recorded stationary on the Neuron-Spectrum-4/VPM hardware complex (Russia, Neurosoft). The electrodes were fixed by "10-20" in 16 active leads of both hemispheres, monopolarly with ear referents. The recording spectrum was 0.5 to 35 Hz. The electrode resistance was less than 5 kOhm. A quantization frequency of 500 points was used. The EEG recording of each stage was analyzed by >20 analysis epochs lasting 10-15 s each, highlighting artifact-free areas. Since EEG recording at all stages of the experiment was performed with open eyes and high mental activity of the subjects, special attention was paid to eliminating oculographic and myographic artifacts. Mathematical analysis of EEG was performed using the Neuron-Spectrum-NET program with Fourier transform for the frequency ranges δ (0.5-4.0 Hz), θ (4.0-8.0 Hz), α (8.0-12.9 Hz), β1 (13.0-20.0 Hz) and β2 (20.0-35.0 Hz). To describe the functional state of the subjects' brain, the full spectrum power (μV^2) averaged over 16 active leads in the given frequency ranges, the integral EEG alpha/theta indices by power were used, and the averaged full spectrum power (μV^2) indicators were identified in the frontal areas of the left (Fp1, F3, F7) and right (Fp2, F4, F8) hemispheres.

Statistical processing was performed using the SPSS Statistics 23 software package. The data are presented as median (Me), first and third quartiles (Q25-Q75). The normality of distribution was tested using the Shapiro-Wilk test. Since the distribution of the indicators did not correspond to normal, the reliability of differences was determined using nonparametric methods: according to the Mann-Whitney criterion for two independent groups when comparing by gender, according to the Wilcoxon criterion for comparing the stages of the Trier test. Differences were considered significant at $p<0.05$.

Study Limitations. The sample size (number of participants) is a limitation of the study. However, it is worth noting that the sample was quite heterogeneous in terms of the representation of young people from different areas of permanent residence. For example, 55% of the subjects permanently resided in the city of Tyumen and the Tyumen region. The remaining 45% were students permanently residing in various regions of Russia: from Nizhny Novgorod in the west and Krasnoyarsk in the east, to Salekhard in the north and Kurgan in the south. The group of subjects was also heterogeneous in terms of ethnic and cultural composition.

3. Results

The full spectrum power in all frequency ranges in the first (control) stage did not have significant differences by gender.

The second anticipatory stage of the Trier test was characterized by a reliable increase in the spectrum power in women in the delta ($Z = 2.72$; $p = 0.006$) (Fig. 1), theta ($Z = 2.86$; $p = 0.004$) (Fig. 2), alpha ($Z = 2.48$; $p = 0.012$) (Fig. 3), beta1 ($Z = 3.07$; $p = 0.002$) (Fig. 4) and beta2 ($Z = 2.48$; $p = 0.012$) (Fig. 5) ranges compared to the control. In men, the stage of expectation and preparation for the performance did not cause significant changes in the full power of the spectrum and was reliably lower than in women in the delta ($U = 107$; $Z = -2.50$; $p = 0.012$), theta ($U = 108$; $Z = -2.46$; $p = 0.013$), alpha ($U = 86.5$; $Z = -3.06$; $p = 0.002$), beta1 ($U = 83$; $Z = -3.15$; $p = 0.001$) and beta2 ($U = 107$; $Z = -2.49$; $p = 0.012$) bands.

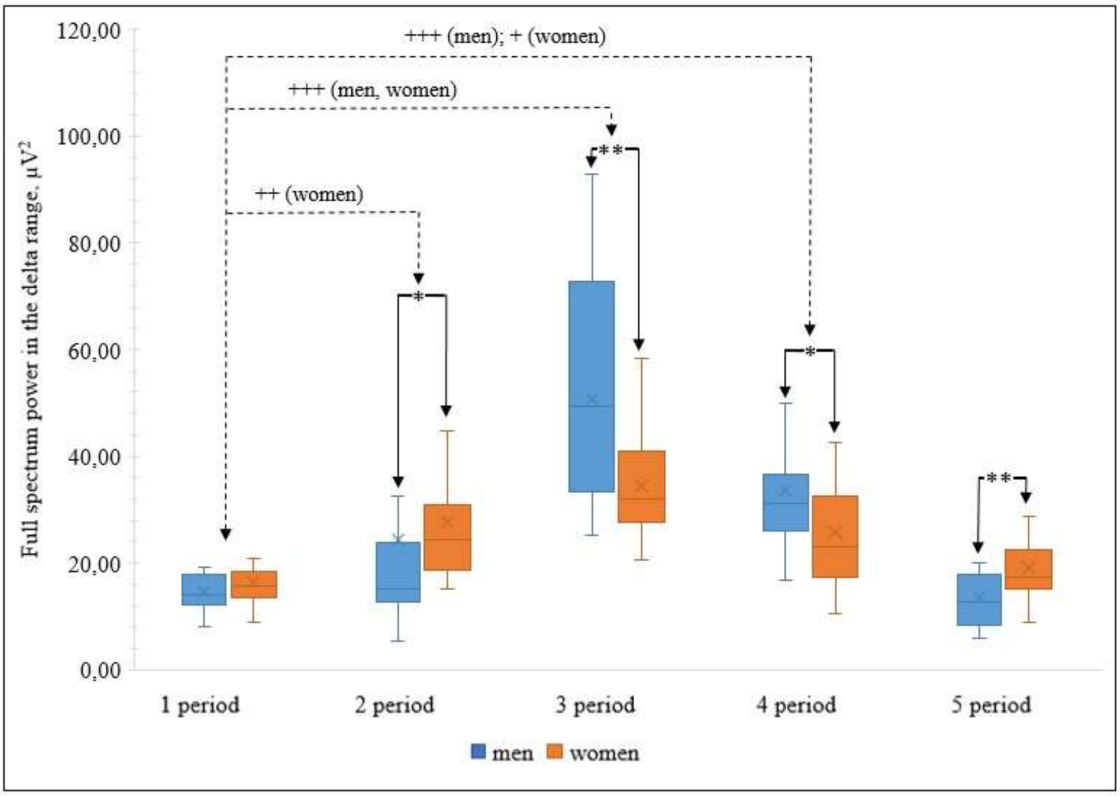

Figure 1. Dynamics of the full spectrum power in the delta range by stations of induced stress (TSST)

Stage 1 – stage of background recording with open eyes in a calm state (control), stage 2 – stage of expectation, preparation for a public speech, stage 3 – reactive stage of a public speech, stage 4 – stage of cognitive stress (countdown), stage 5 – stage of recovery with open eyes in a calm state. Box boundaries correspond to quartiles Q25 and Q75. Lines inside the box are medians. Crosses in the box are mean, upper and lower deviations – maximum and minimum values. Reliability of intergroup differences by gender * - p<0.05; ** - p<0.01 according to the Mann-Whitney method. Reliability of intragroup differences by stress stages with 1 control stage + - p<0.05; ++ - p<0.01; +++ - p<0.001 according to the Wilcoxon method.

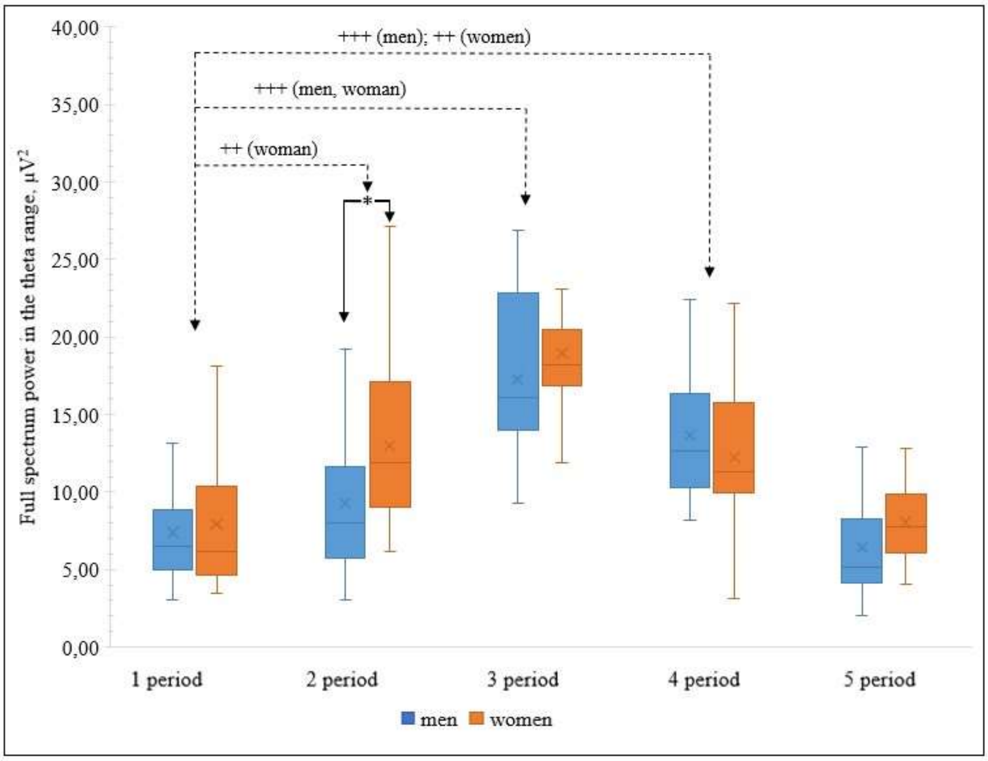

Figure 2. Dynamics of the full spectrum power index in the theta range by induced stress stations (TSST). For designations, see **Figure 1**

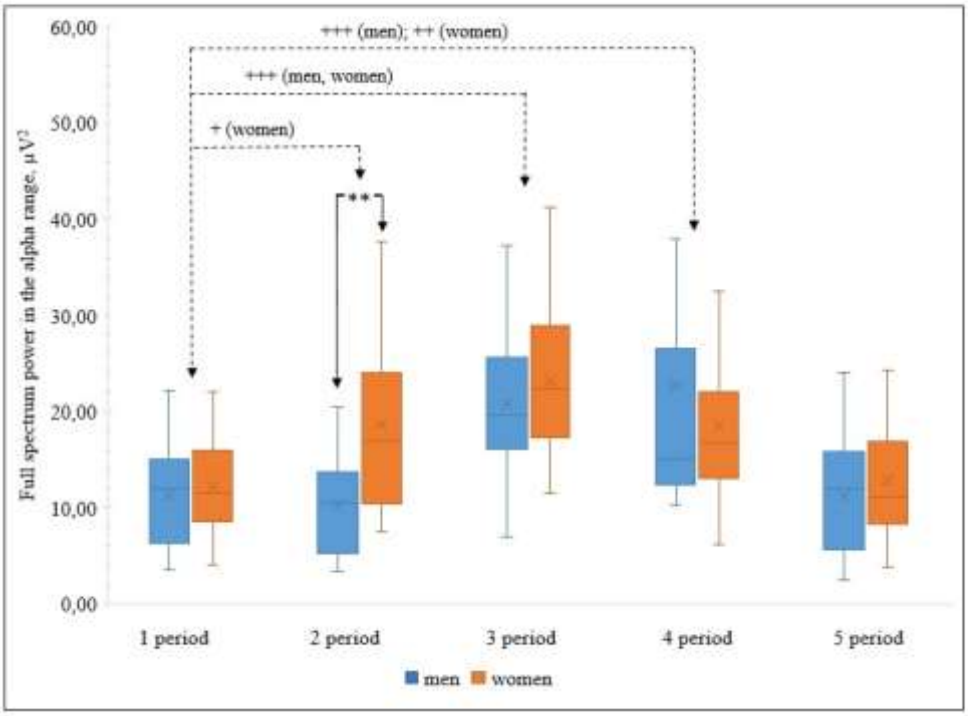

Figure 3. Dynamics of the full spectrum power index in the alpha range by induced stress stations (TSST). For designations, see **Figure 1**

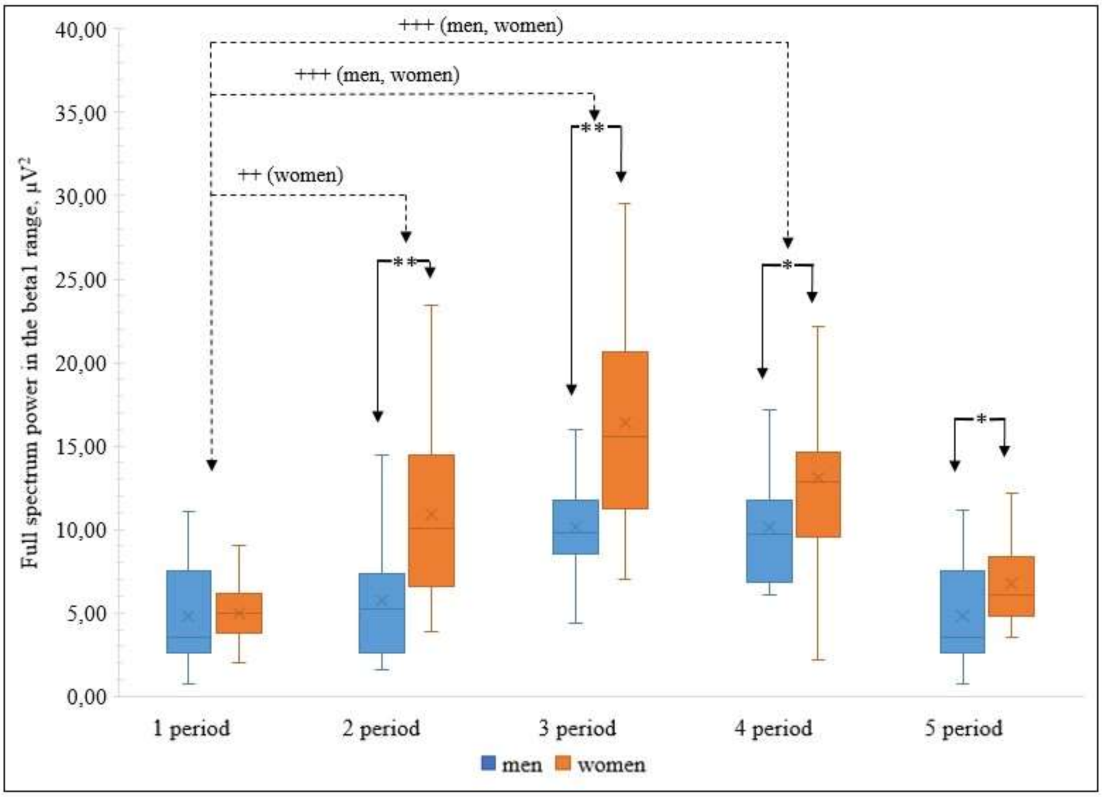

Figure 4. Dynamics of the full spectrum power index in the beta1 range by induced stress stations (TSST). For designations, see **Figure 1**.

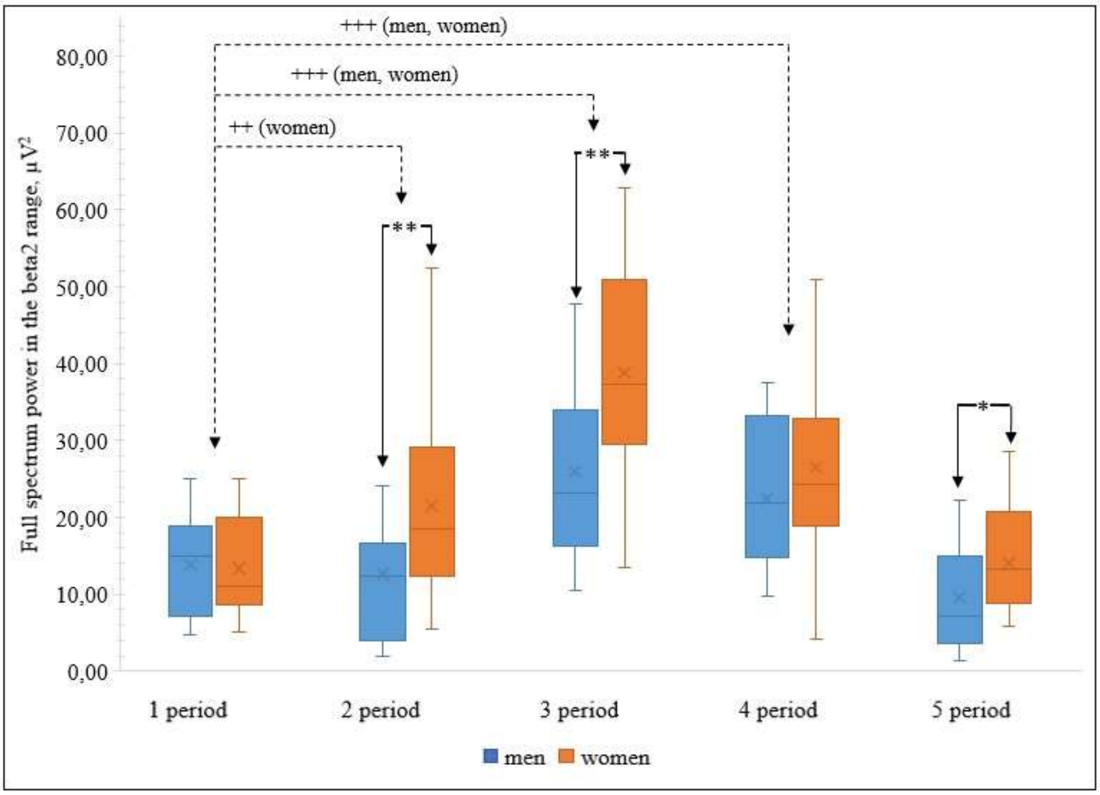

Figure 5. Dynamics of the full spectrum power index in the beta2 range by induced stress stations (TSST). For designations, see **Figure 1**.

The third reactive stage of the Trier test, associated with public speaking and self-presentation, was accompanied by the most significant increase (relative to the control) in the full power of the brain bioelectrical activity spectrum. Moreover, if the increase in power in the slow-wave component was more pronounced in men: delta- (Z = 3.82; p = 0.0001), theta- (Z = 3.82; p = 0.0001), with gender differences in the delta range (U = 99; Z = 2.72; p = 0.006), then the power of the alpha rhythm of the brain increased reliably in both gender groups: men alpha- (Z = 3.58; p = 0.0003), woman alpha- (Z = 3.73; p = 0.0001). The power of the fast-wave component was also significantly higher than the first stage of the TSST: in women beta1- (Z = 3.97; p = 0.0001), beta2- (Z = 4.01; p > 0.0001), in men beta1- (Z = 3.62; p = 0.0002), beta2- (Z = 3.82; p = 0.0001) with differences by gender beta1- (U = 80; Z = -3.23; p = 0.001) and beta2- (U = 92; Z = -2.91; p = 0.003).

The fourth cognitive stage of the TSST had a less pronounced spectrum power profile relative to the previous stage, but significantly exceeded the control values: in men in the delta (Z = 3.78; p = 0.001), theta (Z = 3.74; p = 0.001), alpha (Z = 3.21; p = 0.001), beta1 (Z = 3.70; p = 0.0002) and beta2 (Z = 3.74; p = 0.0001) ranges; in women in the delta (Z = 2.27; p = 0.022), theta (Z = 2.90; p = 0.003), alpha (Z = 2.97; p = 0.003), beta1 (Z = 3.80; p = 0.0001) and beta2 (Z = 3.56; p = 0.0003) ranges with intergroup differences in the delta (U = 119; Z = 2.18; p = 0.029) and beta1 (U = 128; Z = -1.93; p = 0.050) parts of the spectrum.

By the fifth stage of recovery, the full spectrum power in all frequency bands decreased to the initial (control) level, however, in women it was higher than in men in the delta (U = 93; Z = 2.88; p = 0.003), beta1 (U = 114; Z = -2.31; p = 0.020) and beta2 (U = 123; Z = -2.07; p = 0.038) ranges.

The index of stability of cortical electrical activity, determined by us by the ratio of the total spectrum power in the alpha/theta bands[5], was significantly lower than the control in all stages of induced stress, decreasing most significantly at the stage of expectation and the reactive stage of public speaking. There was no reliable return to the initial level of this indicator in the recovery stage either (Table 1).

Table 1. Dynamics of the α/θ rhythm index of the full spectrum power (μV^2) by stages of induced stress, Me (quartiles Q25; Q75)

Trier test stage	Subject group	Me (Q25; Q75)	Reliability of differences with stage 1 (background) according to the Wilcoxon criterion	
			Z	p
1	men	2,25 (1,82; 3,32)		
	women	1,85 (1,42; 2,57)		
2	men	1,10 (1,00; 1,34)	3,62	0,0002
	women	1,31 (1,16; 1,75)	3,11	0,0010
3	men	1,13 (0,79; 1,59)	3,62	0,0002
	women	1,28 (1,04; 1,43)	3,70	0,0002
4	men	1,40 (0,95; 2,31)	2,75	0,0050
	women	1,22 (1,03; 2,01)	1,72	0,0800
5	men	1,71 (1,27; 1,99)	3,67	0,0002
	women	1,53 (1,01; 2,26)	3,91	0,0001

Another EEG indicator of stress reactions – frontal asymmetry of the alpha rhythm was measured and averaged over three frontal leads in the left (Fp1, F3, F7) and right (Fp2, F4, F8) hemispheres. No significant interhemispheric differences were recorded at any stage of induced stress (Table 2).

Table 2. Full spectrum power (μV^2) in the alpha range (8-12.9 Hz) in the frontal leads by stages of induced stress, Me (quartiles Q25; Q75)

Trier test stage	Subject group	Full spectrum power (μV^2) in frontal leads	
		left hemisphere (averaged over Fp1, F3, F7)	right hemisphere (averaged over Fp2, F4, F8)
1	men	12,62 (9,56; 25,51)	13,73 (11,55; 26,43)
	women	13,00 (7,08; 26,24)	11,53 (7,1; 22,11)
2	men	6,56 (5,15; 10,32)	8,96 (5,30; 12,96)
	women	11,64 (6,50; 18,42)	14,58 (9,27; 20,10)
3	men	16,86 (15,51; 21,71)	18,48 (14,27; 19,38)
	women	21,19 (13,94; 26,58)	20,20 (14,26; 25,86)
4	men	13,76 (10,28; 23,50)	12,43 (9,96; 24,62)
	women	14,39 (10,72; 16,79)	13,48 (10,14; 17,96)
5	men	8,99 (4,99; 12,05)	7,88 (5,58; 12,58)
	women	8,74 (6,54; 12,15)	8,87 (7,47; 10,22)

4. Discussions

In our study, the full spectrum power in the delta band increased significantly at all three stages of the stress test. In the work[50], the delta rhythm power increased in the reactive stage of induced stress, which, according to the authors, as well as our assumptions, may be associated with the subjects' prediction of social acceptance/rejection during the test. This effect was especially pronounced in stage 3 of the test at the public speaking stage.

The theta rhythm is often explained by the consolidation and retrieval of memory traces, sensorimotor processing of information, performance of cognitive tasks, and noise immunity[6]. In studies[28, 32], a sharp increase in theta activity is noted in experiments with psychosocial stressors. We also observed a significant increase in theta oscillations in the stages of stress anticipation, the reactive phase, and the cognitive load stage. At the same time, in the recovery phase, theta activity took its original values. In a number of studies[48], an increase in theta activity is associated with the activation of the non-specific component of attention and the strengthening of the individual's orienting and exploratory activity, which may partly characterize the physiological component of the reactive and cognitive stages of psychosocial stress. At the same time, an increase in the power of the "selectively distributed integrative theta system"[8] may correlate with the activation of motivational limbic structures and maintaining concentration on the activity being performed or, on the contrary, indicate a decrease in the inhibitory control of the cortical centers over the brainstem and subcortical structures[3].

The dynamics of the alpha rhythm power in our study was contradictory. In most studies of psychosocial stress[3,19, 30], alpha activity significantly decreased in the reactive stage, which was logically explained by the depression of the main brain rhythm when an individual had to respond to a threatening or uncertain stimulus. In our work, EEG recording was carried out at all stages with open eyes, which in itself caused the suppression of alpha activity, but in the reactive stages of the stress reaction, the full spectrum power in the alpha range increased. We are inclined to believe that this manifestation reflects the general stress excitation of the cortical-subcortical functional associations, including the thalamic generators of the alpha rhythm, developing as a result of partial irradiation of excitation according to a generalized scenario. Because the Trier test stages span short time intervals (300 seconds per stage), it is possible that the generalized increase in alpha power in our study reflects the brain's initial response to the social stressor. However, with longer exposure to the stressor, a decrease in alpha oscillations may be observed, as has been observed by other researchers. It should be noted that in one of the studies[11], the power of alpha oscillations in the reactive phase of stress also increased. A number of studies[9] have noted the specificity of EEG correlates of selective attention when performing tasks with the dominance of mental attention (which was especially characteristic of stages 2 and 4 of our experiment) in the theta and alpha ranges. Thus,[7,36] noted an increase in alpha oscillations during cognitive load and tasks on visual-spatial working memory.

The power of high-frequency beta waves (beta1 and beta2) in our study also increased in the reactive stress stage and returned to the initial level during the recovery period, and in the group of women the dynamics were significantly more pronounced. A similar picture was noted in the studies of other authors[29, 43], which probably characterizes the general activation of the thalamocortical and corticocortical neural networks accompanying intensive information processing in the brain of the subjects.

The ratio of alpha/theta components of the spectrum of bioelectrical activity of the brain in a relaxed state of the subject with closed eyes can be used to describe the balance of cortical activity and neurophysiological correlates of maladaptive manifestations[41], whereas in a situation of open eyes and active activity, which was implemented in our study, the alpha/theta index is used as an indicator of cognitive load and mental performance. In the work[47], the alpha/theta index calculated from averaged EEG channels served as an index of vigilance or an indicator of the subjects' alertness when performing psychomotor tasks. The increase in the concentration of selective attention (vigilance) and cognitive load in a situation of psychosocial stress in our subjects was reflected in the dynamics of the α/θ index of the full spectrum power with the preservation of trace phenomena even at the recovery stage.

The index of frontal alpha rhythm asymmetry, used in studies of EEG correlates of stress reactions[39, 46], reflects the dominant activation of the right hemisphere under the influence of the sympathoadrenal system and accompanies the behavioral reaction of "fight or flight". In our work, the effect of frontal alpha asymmetry was not observed at any of the stages of psychosocial stress, which allows us to assume the situational nature of this neurophysiological manifestation of stress or to consider its absence as a marker of the development of an acute psychosocial situation, accompanied by an approach system, and not an avoidance system. In studies of chronic stress conditions and depressive disorders, the effect of frontal alpha rhythm asymmetry is also far from always detected[27, 14], which the authors explain by the high individual variability of this indicator and the emotional and motivational impact on intragroup variability.

In general, the search for EEG biomarkers of psychosocial stress seems to be an important direction for the development of objective psychophysiological methods for diagnosing the functional state of a person, as well as for the targeted selection of neurobiocontrol characteristics when developing biofeedback training protocols using EEG.

5. Conclusions

The use of the provocative induced stress technique in the modification of TSST allowed us to identify some neurophysiological correlates of acute psychosocial stress. Based on the ideas of a number of researchers[49], who believe that the spectral characteristics of the delta and theta oscillatory systems can be correlated with the activity of the limbic and stem structures of the brain, and alpha and beta oscillations are evolutionarily associated with thalamocortical neural networks, in this work we can assume the involvement of all of the above oscillatory systems in the implementation of the stress response, regardless of their relationship with the subcortical activating structures of the brain. The alpha/theta index indicated the activation of the selective attention system and cognitive load of the subjects during and after the action of stress factors of psychosocial genesis. Psychosocial reactivity in slow-wave components (Δ- and θ-rhythms) of the power spectrum was expressed more strongly in men, while in fast-wave components (β1- and β2-rhythms) – in women. Frontal asymmetry of the alpha rhythm was not revealed during the experiment, which may indicate the situational nature of the occurrence of lateralization of EEG characteristics during stress reactions.

Example of author contributions:

Conceptualization, Tolstoguzov S.N., Savin M.R.; methodology, Tolstoguzov S.N.; software, Savin M.R.; formal analysis, Tolstoguzov S.N., Savin M.R.; writing – original draft preparation, Tolstoguzov S.N., Savin M.R.; writing – review and editing, Tolstoguzov S.N. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare no conflict of interest

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