

Mental Activity of the Brain and Emotional Stress

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Abstract

The article considers the biological nature and origins of emotional stress. Emotional stress is primarily formed in the mental activity of the brain in the form of pronounced long-term negative emotions and is secondarily manifested in neurophysiological mechanisms and somatovegetative processes. However, all studies of the development of emotional stress are focused on the study of central neurophysiological mechanisms, excluding the possibility of analysis for the “sources” of emotional stress, which is primarily formed in the subjective sphere of brain activity, *i.e.*, in the mechanisms of emotions. In our studies, we propose a fundamentally new methodology for studying the mental activity of the human brain and, in particular, the mechanisms of emotions. Thereby, modern methods of psychophysiology make it possible to come closer to understanding the nature of emotional stress.

Keywords

Brain, Emotions, Emotional Stress, Neurophysiology, Psyche, Electroencephalogram, Continuous Wavelet Analysis

1. Introduction

The brain is a unique formation in living nature, with the ability to subjective, mental activity, expressed in feelings, emotions, thoughts, and consciousness [1]-[8].

Emotions, being one of the manifestations of the mental activity of the brain, affect all vital functions of the body. As is known, long-term negative emotions contribute directly to emotional stress [9] [10] [11] [12]. However, since the nature of the mental activity of the brain has still not been disclosed, all studies of emotional stress are focused on the study of central neurophysiological mechanisms without analyzing the “sources” of emotional stress, which is primarily

formed in the subjective sphere of brain activity, *i.e.*, in the mechanisms of emotions [13].

For a deeper understanding of the origin of emotional stress, it is necessary to study its first development in the mental mechanisms of emotions.

2. Emotions and Emotional Stress

Emotions are subjective states that reflect the mental activity of the brain. The “Dynamic Theory of Emotions” formulated by us describes the sequential development of positive and negative emotions at different stages of purposeful behavior, taking into account the changing relationships of predicted probability and real achievement of the result, as well as individual characterological personality traits [14].

Emotions are subjective states of a person or an animal, which depend wholly (qualitatively and quantitatively) on the nature of social or biological needs, the possibilities and reality of satisfying them with purposeful behavior, and are characterized by a complex of somatovegetative reactions.

Emotions cause the appearance of behavioral and somatovegetative reactions [9] [10] [15]. Emotions should be distinguished as subjective states; and emotional reactions, as physiological manifestations of emotions that arise as a result of emotions, in the form of various behavioral and somatovegetative manifestations.

The concept of stress as a general non-specific adaptive syndrome of the body was first formulated in the works of H. Selye [16] [17].

According to H. Selye’s definition, stress is a reaction that arises as a nonspecific response of an organism to the action of extreme, adverse environmental factors, or “stressors”, that are pathogenic agents, toxic and foreign substances, physical factors, and other inappropriate influences. In all cases, the stress reaction is formed due to the activation of the pituitary-adrenal mechanisms, including the activation of ACTH and the adrenocortical function of the adrenal glands.

According to its biological purpose, stress has an adaptive focus and activates protective mechanisms to prevent the pathogenic effect of adverse factors on the body. A dual nature characterizes stress, which is adaptive and pathogenetic. A series of successive stages: anxiety, resistance, and exhaustion, characterize stress. The last stage ends with the death of the body.

Along with the concept of stress, science has developed an idea of emotional stress as a psychoemotional state of a subject, which is characterized by a complex of nonspecific (concerning the initiating emotiogenic factor) behavioral, autonomic, and hormonal manifestations [18] [19] [20].

Primary emotional stress is formed in the mental activity of the brain as a result of pronounced, prolonged negative emotions arising in a conflict behavioral situation [13] [21]. Given this, we can define the concept of emotional stress as a complex of psycho-emotional and somatovegetative reactions of the body that

arise in a conflict behavioral situation when humans and animals cannot satisfy their leading biological or social needs.

The development of emotional stress depends on the individual subjective perception of the proneness to conflict in the prevailing behavioral situation. A conflict situation arises only when the individual perceives it in this way.

Emotional stress is nonspecific concerning any conflict situation complex of reactions affecting vital physiological functions.

Systematic dissatisfaction in the results of behavior, associated with the lack of the subject's ability to achieve an adaptive result, generates a prolonged continuous negative psychic tension, *i.e.*, emotional stress. At the same time, emotional reactions lose their adaptive character, and disturbances in physiological functions arise, leading to the development of psychosomatic diseases.

Biomedical and psychophysiological studies convincingly show that emotional stress has an overall effect on the vital functions of an organism and undermines people's health. Emotional stress may be the cause of many psychosomatic diseases: psychosis, neurosis, sleep disturbances; cardiovascular diseases, *i.e.*, arrhythmias, extrasystoles, myocardial infarction, hypertension; ulcerative-dystrophic lesions of the gastrointestinal tract; decreased immunity and increased susceptibility to viral and infectious diseases; autoimmune processes; rheumatic diseases, osteochondrosis; oncological diseases; hormonal and sexual dysfunctions, etc. [15] [22] [23] [24].

Along with vegetative-visceral manifestations, emotional stress can cause severe psychoneurotic reactions with disturbance of conduct; excessive mistrustfulness, anxiety, suspicion appear, a tendency to long-term emotional experiences arises, sleep is disturbed, working capacity is reduced, and memory is impaired. Emotional reactions lose their plasticity and cease to be adequate factors in mobilizing behavior to satisfy a specific adaptive result. The symptom complex of neurotic reactions in animals that develops as results of emotional overstrain is also well known: impaired conditioned activity, decreased learning ability, sleep disturbances, etc. [11] [23] [25] [26].

Stress affects the genetic apparatus of cells, leading to congenital disorders in the children's development and health. The detrimental effect of stress is manifested in the growth of alcoholism and drug addiction, in the increase in injuries, growing number of suicides, in the incapacitation of society. Emotional stress is the main reason for reducing life expectancy, increasing mortality, and, in particular, sudden death [11] [27] [28].

3. Central Neurophysiological Mechanisms of Negative Emotional Reactions and Emotional Stress

Emotional reactions are primarily formed in the hypothalamic-limbic-reticular structures of the brain, and along the ascending path, it generalizes to the cerebral cortex, and in the downstream direction, it involves the autonomic nervous system, stimulates the hormonal activity of the pituitary-adrenal mechanism

[10] [13] [24].

Limbic structures of the brain are involved in the formation of emotional reactions. These include areas of the ancient and old cortex, as well as some fields of the new cerebral cortex (orbital, part of the temporal cortex), most of the diencephalon, reticular formation, and midbrain.

The hypothalamus has a principal function that determines the appearance of various biological motivations in the event of metabolic needs. It is that “pace-maker point” that triggers the activity of brain structures necessary for highlighting the dominant motivation, assessing situational afferentation, and determining the possibility of satisfying a real need.

Among the hypothalamic structures involved in the formation of behavioral and somatovegetative components of adverse emotional reactions, a special role belongs to the ventromedial nucleus of the hypothalamus. In animal experiments, it was shown that local electrical irritation of the ventromedial hypothalamus in immobilized animals causes a complex of behavioral manifestations characteristic of adverse emotional reactions. During emotional reactions of hypothalamic origin, first of all, changes in bioelectrical activity occurred in the emotiogenic structures of the brain [13].

Our studies have first shown that adverse emotional reactions cause changes in the chemical sensitivity of neurons of the medial hypothalamus, medial thalamus, and reticular formation of the midbrain to the mentioned neurotransmitters and neuropeptides [21] [29].

Subtle molecular rearrangements induced by emotional reactions occur in the synaptic apparatus of neurons, manifesting themselves in a change in the structural and functional properties of synaptic membranes, transport, and reception of neurotransmitters. Changes in the chemosensitivity of neurons can be mediated by changes in the conformational structure of receptor proteins, as well as a change in the number of functioning receptors.

Emotional stress primarily arises as a central neurogenic process. During emotional stress in the emotional structures of the brain, changes occur in the content of the primary mediators such as norepinephrine, acetylcholine and serotonin. The most pronounced change in catecholamine content during emotional stress occurs in the hypothalamus and is characterized by a decrease in norepinephrine and an increase in dopamine content [12] [30].

The change in the content of catecholamines in different brain structures is associated with the restructuring of catecholamine metabolism during emotional stress, which depends on the rate of synthesis, utilization, and reuptake of biogenic amines, as well as on the activity of enzymes of catecholamine metabolism.

The most characteristic central sign of emotional stress is a decrease in the content of noradrenaline in the hypothalamus. The increase and normalization of the amount of noradrenaline in the hypothalamus correlate with resistance to emotional stress.

In chronic stress with subsequent adaptation, normalization of noradrenaline in the hypothalamus reduced under the influence of acute emotional stress oc-

curs, as well as an increase of noradrenaline in the midbrain, and dopamine in the hypothalamus and the medulla oblongata.

An essential condition for adaptation to emotional stress is the body's ability to restore normal levels of noradrenaline in the hypothalamus, increase its content in the midbrain, and also increase dopamine levels in the hypothalamus, midbrain and medulla oblongata.

Animals adapting to emotional stress demonstrate a specific rearrangement of the catecholamine metabolism, against which an additional single emotional impact does not cause changes in the content of noradrenaline, dopamine, and serotonin in the brain, similar to those that occurred during acute emotional stress [30].

In our studies, we first began to study the role of several endogenous peptides in the central mechanisms of emotional stress. It was shown that endogenous peptides synthesized in the brain, Substance-P (SP), prolactin (PRL), are involved in the neurochemical mechanisms of emotional stress. The effect of SR and PRL is manifested in the modulatory effect on the metabolism of catecholamines in the brain during emotional stress [29].

The neurochemical mechanisms of emotional states are based on the selective reorganization of neurochemical properties and plastic rearrangement of the neurotransmitter metabolism of neurons in the emotional zones of the brain, resulting in the formation of a new neurotransmitter integration of emotional excitation that determines the existence of a negative emotional state, which triggers the whole complex of somatovegetative manifestations of emotional reactions [14].

Different neurotransmitter mechanisms simultaneously participate in the neurotransmitter integration of negative emotional excitation: adreno-, choline- and serotonergic processes, and nor can it be attributed to any specific process a specific function in the neurotransmitter support of negative emotional states. The neurotransmitter integration of the emotional state is polychemical in its neurochemical organization.

The neurochemical integration of negative emotional excitement is a branched apparatus, which includes the interaction and participation of various oligopeptides, neurotransmitters in synaptic, metabolic processes in the neurons of the emotiogenic structures of the brain.

Scientific research resulted in the idea of the central neurophysiological mechanisms of emotional stress. However, the "sources" of the development of emotional stress in the mental sphere, to which emotions belong, were left out of the field of view of researchers.

4. The Mental Activity of the Brain

Understanding of nature of the mental activity of the brain is the most urgent and most challenging task of physiology [3] [6] [31] [32] [33].

The theory of functional systems developed by P. K. Anokhin, and widely

represented in the works of many other researchers, “paves the conceptual bridge” between the mental and neurophysiological activities of the brain and points to the central nodal mechanisms that are associated with the formation of purposeful behavior and the origin of emotional and thought processes [15].

At the same time, only the neurophysiological component of brain processes is reflected in the functional system, while the mental activity of the brain, which remains literally “behind the scenes”, is not represented; it is only implied that it exists.

Systemic organization of the neurophysiological and mental activity of the brain (Figure 1) has two interconnected and integrated into a single whole sub-system: neurophysiological and mental [7] [8].

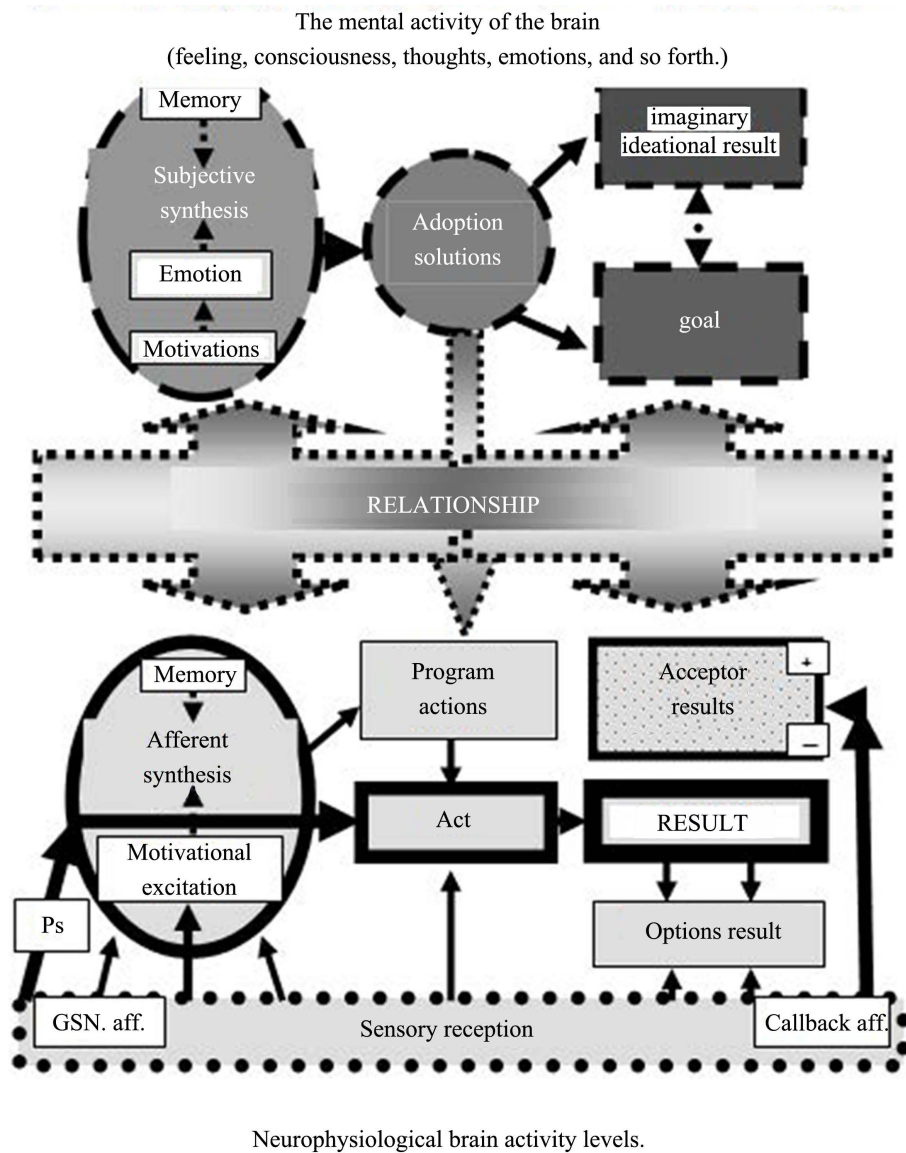


Figure 1. The scheme of the functional system of goal-seeking behavior: interaction of neurophysiologic (1) and subjective (2) processes in the brain activity. Legend: P.s.—trigger stimulus, GSN. aff.—situational afferentation. Callback aff.—reverse afferentation.

The structural and neurophysiological component of a functional system cannot carry out its productive activity without the participation of the mental sphere, just as mental activity is formed based on neurophysiological processes.

The neurophysiological level is the basis for the perception of the environment and the internal state of the body, as well as for the implementation of various forms of behavior and regulation of the life of the body.

At the neurophysiological level, all sensory excitation flows from the sensory organs are perceived, biological motivations, neurophysiological components of memory associated with memorizing and storing information, efferent, command programs that control movement, behavior and autonomic reactions are formed, reflex reactions, automated behavioural acts are performed, and due to the previously established pretest integration, the obtained result is evaluated.

At the mental level, understanding of all the information entering the brain is carried out, social motivations are formed, the necessary information is extracted from the memory, the goal appears, and all psychological manifestations arise, such as consciousness, thinking, emotions, etc. The main mental functions of the brain: free will, goal setting, choice of behavior, mental, imaginary result, and assessment of goal achievement occur at an individual conscious level.

The mental and neurophysiological activities of the brain are interconnected, and the relationship between them is two-way. At the same time, there is still a huge gap between knowledge in the field of brain neurophysiology and ideas about its mental functions. It explains the “gap” in the understanding of mental and neurophysiological phenomena in the brain, which is indicated by T. Nagel.

When analyzing the problem on the origin of a subjective state, T. Nagel wrote:

“...describing mental phenomena, ‘subjective reality’ and coupling them with the neurophysiologic processes faces the ‘explanation gap’. The parallel description of the neurophysiologic processes and mental states caused by them (?) or accompanied by them (?) does not help answer the question how the behavior of a neuron network produces the subjective states, feelings, self-reflection and other phenomena of high order. Without the change of the fundamental concepts of the consciousness, the explanation gap cannot be overcome” [32].

In our studies, we proposed a fundamentally new methodology for understanding the nature of the mental activity of the brain and, for the first time, formulated the paradigm of the mental activity of the brain [7] [8].

Undoubtedly, without an understanding of the mental activity, all ideas about the functioning of the brain are inconsiderable and very far from the truth. Without recognizing the mechanisms of emotions in the mental activity of the brain, it is impossible to recognize the nature of emotional stress.

Despite the tremendous achievements of modern neurophysiology, existing methods do not allow direct recording and studying patterns of mental activity of the brain [5] [7] [8] [32].

In this regard, a fundamental question arose: is it possible to reveal manifestations of purely mental activity in the electroencephalogram (EEG) of the human

brain?

Revealing the nature of the mental activity of the brain requires developing a fundamentally new information methodology that allows deciphering the manifestations (patterns) of the mental activity of the brain in the neurophysiological processes.

4.1. Recognition of Psychic Brain Activity with Continuous Wavelet Analysis of EEG

Currently, a progressive mathematical method of continuous wavelet analysis of EEG has been developed, which opens up new possibilities for identifying the information content of brain processes and, in particular, in decoding EEG [34] [35] [36] [37].

Continuous wavelet transform has a significant advantage over the classical method of spectral analysis of EEG since it allows the time-frequency analysis of complex non-stationary signals, one of which is EEG. At the same time, the question of whether it is possible to reveal manifestations of the mental activity of the brain in the EEG remained open.

4.1.1. Calculations

Continuous wavelet transform (CWT) is used for analysis of obtained EEG data. CWT is known to be effective in time-frequency analysis of nonstationary signals (including EEG) and as basis for development of algorithms for automatic detection of specific EEG patterns.

CWT is a convolution of analyzed signal $x(t)$ and set of basic functions $\varphi_{s,\tau}$:

$$W(s, \tau) = \int_{-\infty}^{+\infty} x(t) \varphi_{s,\tau}^*(t) dt, \quad (1)$$

where the asterisk denotes the complex conjugation. Each basic function $\varphi_{s,\tau}$ from this set is obtained by compression/extension and time shift of one function called mother wavelet as following:

$$\varphi_{s,\tau}(t) = \frac{1}{\sqrt{s}} \varphi_0\left(\frac{t-\tau}{s}\right), \quad (2)$$

where s —time scale responsible for compression or extension of mother wavelet, τ —time shift of wavelet function, φ_0 —mother wavelet. Instead of time shift s it is possible to introduce frequency $f = 1/s$, which is more convenient in terms of time-frequency analysis.

The CWT-based spectral analysis of biological signals including EEG is usually performed with the Morlet wavelet as the mother function [38], since Morlet wavelet provides good resolution both in time and frequency domains:

$$\varphi(\tau) = \pi^{-0.25} \exp(j\omega_0 t) \exp(-\tau^2/2) \quad (3)$$

The Morlet wavelet represents the complex harmonic oscillating function, $e^{j\omega_0 t}$, modulated by the Gaussian function, $e^{-\tau^2/2}$. The parameter ω_0 is central frequency of Morlet wavelet, it is usually chosen to be $\omega_0 = 2\pi$ as such value leads to the simple correlation between frequency and time scale: $f = 1/s$. Morlet

wavelet with chosen parameters provides means to analyze short fragments of data series (3 - 5 oscillations) and, therefore, can be used for analysis of different types of EEG patterns.

The most common part of CWT-based signal analysis is investigation of wavelet energy spectrum $E(f_s, t)$ which provides information about time-frequency structure of signal.

$$E(f_s, t) = |W(f_s, t)|^2 \quad (4)$$

Wavelet energy spectrum $E(f_s, t)$ can be averaged over some specific frequency range in order to analyze time dynamics in this range.

For more detailed analysis of frequency dynamics in signal at given time moment t_0 momentary wavelet energy distribution E_{t_0} is used:

$$E_{t_0}(f_s) = |W(f_s, t = t_0)|^2 \quad (5)$$

Investigation of main frequencies in signal can be performed with another CWT-based technique—construction of skeletons. Skeletons of wavelet surface are obtained by picking few local maxima from momentary wavelet energy distribution E_{t_0} and repeating this process for each time moment in the signal. Resulting skeletons can be used for tracking the most significant frequency components in the signal and for analyzing their time dynamics. Such technique provides information about appearance/disappearance of certain specific rhythmic components, which can help to investigate shifts in subject's perception.

Since the main aim of the present paper is to distinguish two types of brain activity on EEG (conscious perception of visual image and absence of this perception) Wilcoxon signed-rank test is used. Wilcoxon signed-rank test is a non-parametric statistical hypothesis test used to compare two related samples to assess whether their population mean ranks differ [39].

4.1.2. Results

Based on an improved method of the continuous wavelet transform [34] [35] [36] [37], we performed an EEG analysis when testing a person's temporary visual discriminatory ability to recognize the semantic content of an image on a monitor screen [40] [41] [42] [43].

During experimental work, EEG are recorded for 10 subjects in the age of 18 - 45. Each subject observes 10 series of 25 images with subsequently shortened demonstration time. Example of EEG recordings is illustrated on **Figure 2**.

Figure 2 shows EEG for 10 channels (O2, O1, P4, P3, C4, C3, F4, F3, T4, T3) with special marks for start and end of demonstration of each image. Thus, EEG episodes during demonstrations of images and between demonstrations can be analyzed in order to test human's visual discrimination ability to realize content of observed image.

EEG are investigated with CWT-based methods. For each channel from EEG recording wavelet spectrum, skeleton and averaged wavelet energy distribution are constructed (see **Figure 3**). **Figure 3(a)** shows initial EEG from one channel

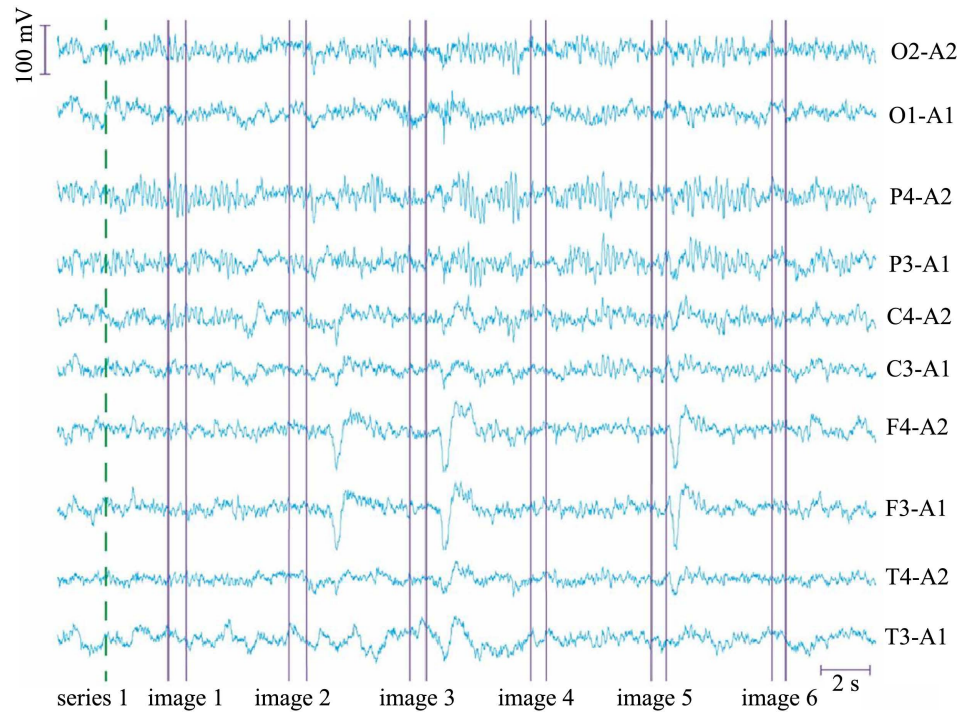


Figure 2. Example of EEG recording for 10 channels during perception of visual stimuli: green dashed marker corresponds to the start of series; dark blue solid markers correspond to the start and the end of presentation of each image in series.

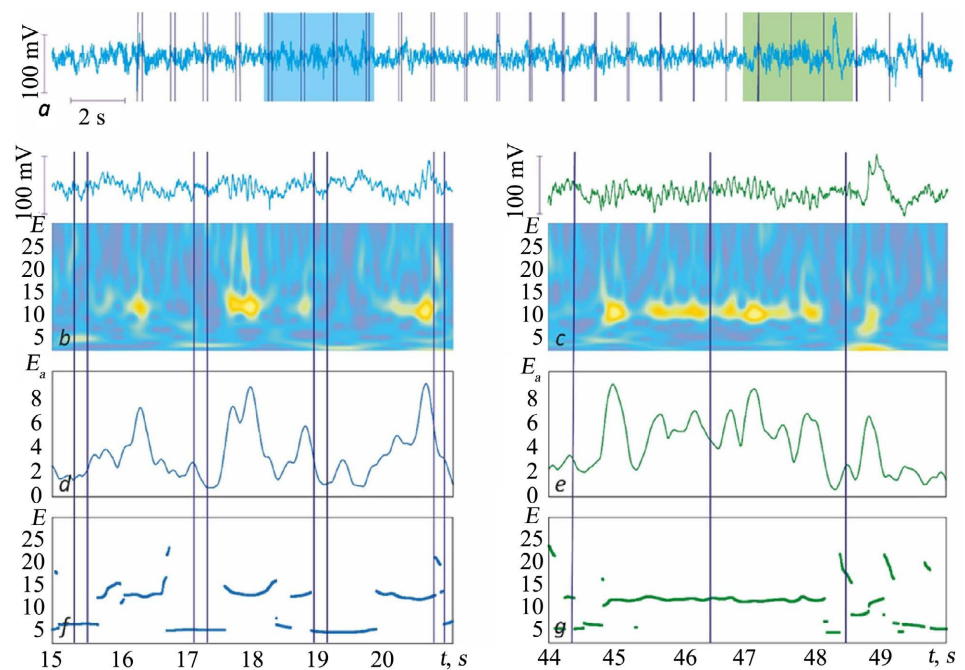


Figure 3. Results of EEG time-frequency analysis: (a) initial EEG signal; dark blue vertical lines mark the start and the end of each image's demonstration, light blue and light green frames correspond to EEG episodes with and without recognition of images; ((b), (c)) EEG episodes and wavelet spectrums for cases with and without recognition of images; ((d), (e)) averaged wavelet energy distributions for cases with and without recognition of images; ((f), (g)) skeletons of wavelet surface for cases with and without recognition of images.

(O1) during one series of image demonstration with dark blue vertical lines that mark the start and the end of each image's demonstration. Two specific EEG episodes are marked on **Figure 3(a)** as examples: the first one where subject recognizes presented images well (marked with light blue frame) and the second one where subject fails to recognize images (marked with light green frame). **Figures 3(b)-(g)** demonstrate results of time-frequency analysis of these two episodes with wavelet-based methods: wavelet spectrums (**Figure 3(b)** and **Figure 3(c)**), distribution of wavelet energy averaged over alpha frequency range (**Figure 3(d)** and **Figure 3(e)**), skeletons (**Figure 3(f)** and **Figure 3(g)**).

Distributions of wavelet energy (wavelet spectrum) are demonstrated in the lower part of **Figure 3(b)** and **Figure 3(c)** alongside with the initial EEG. Wavelet spectrum as projection of surface of wavelet energy distribution on " $t-f$ " plane provides general information about time-frequency structure of EEG. As seen from **Figure 3(b)** and **Figure 3(c)** there are several dominant frequency components on the signal: 2 - 5 Hz component that corresponds to delta frequency range, 8 - 14 Hz—to alpha activity and 15 - 30 Hz—to beta activity.

Figure 3(b) and **Figure 3(c)** one can clearly see that alpha rhythm appears and disappears through EEG recording, which is assumed to be connected with human's ability to realize content of observed image [44] [45].

Thus, distribution of wavelet energy averaged over alpha frequency range (see **Figure 3(d)** and **Figure 3(e)**) can be considered in order to provide more detailed analysis in alpha range.

Figure 3(d) and **Figure 3(e)** demonstrate that alpha rhythm has number of high-energy spikes with certain drops between them. Such shifts correspond to moments of appearance and disappearance of alpha rhythm. For more clear representation averaged wavelet energy is accompanied with skeletons of wavelet surface (see **Figure 3(f)** and **Figure 3(g)**). Skeleton provides information whether or not alpha rhythm is the dominant frequency at given moment and when it loses its dominant status.

From **Figures 3(d)-(g)** one can see that spikes of alpha activity mostly correspond to time moments before and after demonstration of image and alpha rhythm is the dominant EEG frequency at these moments. At the same time, alpha rhythm activity almost completely disappears (drop in average wavelet energy distribution and dominant EEG frequency component changes to delta or beta) during perception of images with long demonstration time (200 - 300 ms).

Analysis shows that in the case of images with short demonstration time (~0 ms) decrease and subsequent increase is far less significant. For example, the second EEG fragment (**Figure 3(c)** and **Figure 3(e)** and **Figure 3(g)**) shows that alpha activity suffers no substantial decrease or increase for images with very short demonstration time.

Thus, all image demonstrations can be divided into two groups: 1) with increase in alpha activity before and after demonstration and considerable decrease during demonstration (case of **Figure 3(b)** and **Figure 3(d)** and **Figure**

3(f)); 2) without described dynamics in alpha frequency range (case of **Figure 3(c)** and **Figure 3(e)** and **Figure 3(g)**). It is assumed that dynamics of the first type corresponds to cases when the subject is possible to realize semantic content of the image while dynamics of the second type reflects the absence of conscious (subjective) perception.

After each series of image demonstration, the subject is asked to pick the time moment t_{cr} when he/she recognizes the previous image and doesn't recognize the next image. This time moment can serve as a possible milestone that separates the state with ability to subjective perception from the state without this ability.

In each series image demonstrations are divided into two groups (two related samples): before moment t_{cr} (possible state of subjective perception) and after moment t_{cr} (possible state with lost ability for subject perception). For these two groups statistical analysis is carried out with use of Wilcoxon signed-rank test. In this analysis the intensity of alpha activity during image perception is compared for these two samples. Wilcoxon criterion is calculated and appears to be $P \ll 0.05$. This result implies significant difference in intensity of alpha rhythm in the state with conscious perception and the state without it.

The wavelet analysis of fragments of the EEG recording shows that the main rhythm of the EEG, which can be used to judge the presence of subjective perception of the visual image, is the alpha rhythm. Significant differences in the dynamics of the EEG alpha rhythm were revealed when the subject was aware of the semantic content of the image and in the absence of a conscious (subjective) perception of the semantic content of the image.

The conducted studies have led us to an important conclusion about the theoretical possibility of revealing the mental activity of the brain in the EEG. Thereby, the prospect of revealing the role of emotions in the formation of emotional stress in the mental activity of the brain has opened.

5. Conclusions

Emotions are one of the forms of mental activity of the brain, which has specific biological laws.

The source of the development of emotional stress is long-term negative emotions and related mental impairments of the brain: neuroses, mental disorders, irritability, aggressiveness, depression, anxiety, sleep disorders.

Emotional stress is primarily formed within the mechanisms of mental activity of the brain and is already secondarily manifested in neurophysiological mechanisms and somatovegetative processes.

The "key" to understanding the nature of emotional stress lies in the mental activity of the brain, in the mechanisms of emotions. Understanding the origin of emotional stress requires knowledge of the nature of the mental activity of the brain and, in particular, the mechanisms of the development of emotions. Modern advances in psychophysiology allowed us to approach the solution to the problem of emotional stress.

Conflicts of Interest

The authors declare no conflict of interest.

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