Evoked Brain Oscillation During Successive Sensory Stimuli Presentation of Different Significance and Modality

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Abstract

Fluctuations of the spindle-like brain oscillations of the range of 1-15 Hz in wakefulness reflect the dynamics of brain microstates and are responsible for cognitive functions. The frequency and periodicity of the rhythm's superposition depends on attention, memory, decision making, the significance and modality of stimuli, emotions and motivations. Our results have shown that evoked delta and theta brain oscillations makes a different contribution to the main components of event related potential (ERP) for target and ignored stimuli. It was sown that the target stimulus analysis was accompanied by an increase of delta wave in the central end parietal brain areas and by a decrease of the theta pattern in frontal brain areas. In contrast, the ignored stimulus was accompanied by a decrease of the evoked delta wave and by an increase of theta pattern, which corresponds to the basic ERP`s components potential. Evoked alpha oscillation possesses by two focuses of activity: the frontal foci one is formed in response to an ignored stimulus, and the parietal-occipital foci, that is formed in response to a target stimulus. In present article, we discussed the functional role of delta, theta and alpha evoked oscillation of the human brain depending on modality, significance (target and ignored stimuli) and also the influence on their successive presentation.

Keywords: Attention, perception, theta, delta, brain activity, ERP

1 Introduction

Brain oscillation forms a hierarchy of coordinated activity at different frequencies. Thus, cognitive processes such as memory, attention, decision making modulating behavioral responses and brain oscillation [1]. This is reflected in the increasing or suppressing of the detection of external or internal stimuli [2]. Exogenous sensory stimulation leads to synchronization or desynchronization of the brain activity of neighboring regions at corresponding to various frequencies. Finish of sensory stimulation leads to decreasing all of evoked brain activity. It is known that the frequency and periodicity of the rhythm's superposition depends on the level of wakefulness, attention, the significance and modality of stimuli [3].

Exogenous sensory stimulation leads to periodic brain fluctuations, which matches with the basic brain oscillations and are reflected variation of behavioral responses. Brain oscillation could facilitate the information processing in the brain by the different ways. One of this way is the creating a flexible temporal reference frame, which consist at the hierarchical organization of oscillations between neuronal populations (or sensory input) [3]. Spatial attention defines a set of cognitive mechanisms that filter irrelevant information and incoming modulated behavioral responses. These results allow to discuss the mechanisms of interaction between evoked brain oscillation and their influence on the behavior.

In literature described the main evoked brain oscillations, which differ from their frequency, amplitude, origin and they are modulated by different parameters of exogenous sensory stimulation. Cross-frequency, phase-amplitude and phase-phase interactions between different brain oscillation are known, ant its plaid an important role in linking various oscillatory processes [4]. Cross-frequency interactions are most studied in the cerebral cortex [4, 5, 6].

Connections between neuronal oscillations in certain frequency ranges and cognitive functions are described in modern studies. Brain oscillation in the delta band (~0–4 Гц), theta band (~4–8 Hz), alpha band (~8–12 Hz), beta band (~13–30 Hz) and gamma oscillations (> 30 Hz) coordinate various aspects of behavior [4, 7, 8].

Earlier studies shown that fluctuations in the delta range were considered as indicator of deep stage of sleep and states of brain disturbances [9, 10]. Recently, arrived a number of hypotheses concerning the relationship between delta oscillations and (1) the control under the neuronal excitability [11, 12], (2) the mechanistic role in sensory signals enhancement, (3) the control and using of attention processes [1, 13], increasing the vigilance paradigm [14]. Slow low-frequency oscillations generated by the cortex are effective for grouping [8, 10], or modulating of other brain high-frequency oscillations [15] due to cortico-cortical and cortico-thalamic pathways.

The phase-reset of the low-frequency delta oscillations may help us to explain the increased attentional performance during sensory stimulation. A contingent negative wave replying to a warning stimulus reflects a reset of the phase of low-frequency delta oscillations in the frontal regions of the brain. Inhibition of return or the effect of attention blinking are related to the phase of low excitability oscillation, which is reset before target stimulus will be presented, or to which attention will be drawn to the next stimulus. Lacatos et al. [11] showed that the delta oscillation in the primary sensory areas of the cortex reflects the processes of attention and also determines momentary power in higher-frequency activity. Therefore, it can be assumed that the delta oscillation in a wakefulness and exogenous stimulation can participate to the processes of the attention modulation.

Landau and Fries [16] showed that phase variability of brain oscillations in the theta and alpha band was associated with visual perception and attention. Exogenously induced fronto-parietal theta synchronization (6 Hz) significantly improves time reaction in a task with working memory, while theta desynchronization impairs efficiency [17]. The connection between the frontal-parietal brain areas of theta oscillation and the processes of recognition, short-term retention and planning was shown in articles [18, 19]. Oscillations in the theta band are associated with the phase encoding of spatial information in the hippocampus and with the formation of neuronal representations during the formation of a trace in memory [20]. Synchronization of theta phase dynamically coordinates the central executive circuits, including the medial prefrontal cortex and parietal regions [19].

Fluctuations of the alpha bands are a measure of excitation at the rest states [21], which are associated with amplitude modulations of sensory and cognitive ERP components [8, 22, 23]. From a functional point of view, evoked alpha oscillations suppress non-target tasks [24, 25], that is effectively declines flows of relevant and irrelevant information [18]. It is known that evoked alpha oscillations respond to various cognitive tasks: perceptual, working and long-term memory, attention, and also demonstrate modulations at the preparatory stage [24, 26]. Suppression of evoked alpha activity in related areas of sensory processing in the absence of increased alpha activity and in the absence of attention has also been reported [1]. Moreover, Mathewson et al. [27] proposed the pulsed inhibitory account, that according to alpha oscillations modulate selection attention ang cognition control. Alpha band represents the alternation of microstates of inhibition and excitation. Therefore, in conditions of wakefulness alpha activity can reflect the work of the processes of attention [28, 29] and inhibition [30, 31].

By origin the mechanism of interaction of brain rhythms consists of instant and delayed interactions with current brain oscillations through synchronization (or desynchronization) of excitation activities in one or more populations of neurons that generate these oscillations. Synchronization of brain oscillations in specific frequency ranges leads to changes in perception, attention and working memory, which could be explained by using multiplexing theories [3] or the relationship of rhythms [32].

Supposed that the phase-amplitude coordination of brain rhythms is one of the mechanisms of brain functioning, which underlies of attention [5, 12, 13, 16], selective attention [24, 31] and filtering information [5]. This coordination could quantitatively determine the relationship between the phase of the envelope of the low-frequency signal and the amplitude of the high-frequency signal.

There is an opinion that low-frequency brain oscillations serve as temporary frames integration for higher-frequency brain activity [13, 33, 34, 35]. It is known that phase-amplitude communication in the brain occurs in both the hippocampus [36] and the neocortex [5, 13], which makes it possible to process and transmit information along the hierarchy of the frequency band [12]. The modulation index is used to measure the intensity of the phase-amplitude coupling [37].

The hypothesis of the connection of cerebral oscillations through the coherence suggests that the transfer of information from one brain area to another occurs with temporarily equalized low-frequency oscillations [32]. In contrast, the inhibition gating hypothesis suggests that low frequencies periodically suppress information in the neuronal population [28]. However, the presence [8] or absence [5, 13] of phase-amplitude coupling is currently under discussion.

It is assumed that working in the rhythmic range entails the participation of mechanisms of various types [2]: 1) sensory cortical involvement (phase synchronization) in the temporal structure of the serviced stream, 2) coordination of phase oscillations with high excitability with events in the serviced stream, and 3) systematic improving responses to simultaneously stimuli or suppressing responses. Consequently, brain oscillations could facilitate information processing in the human brain in various ways, creating a flexible dynamic system operating on the principle of superposition / synergy or multiplexing [3, 14, 15].

At the neuronal level, brain oscillation reflects periodical changes in their activity [39]. Brain oscillations usually refer to local field rhythmic oscillations and reflect the synchronous work of transmembrane channels in local populations of neurons. Thus, there are periodical changes in the excitability and inhibition of such neuronal ensembles. The grouping process leads to different types of slow and fast oscillations in the brain and reflects the functioning of the mechanisms of synaptic plasticity [10].

Fluctuations of brain activity have been studied for a long time, but the role and functional significance of the evoked brain rhythms, especially in their cross-frequency interaction, remains understanding. Present work is devoted to investigation of the cross-frequency interaction of the evoked brain activity by using successive sensory stimulation of various modality (visual and auditory) and different significance (ignored and target stimulus).

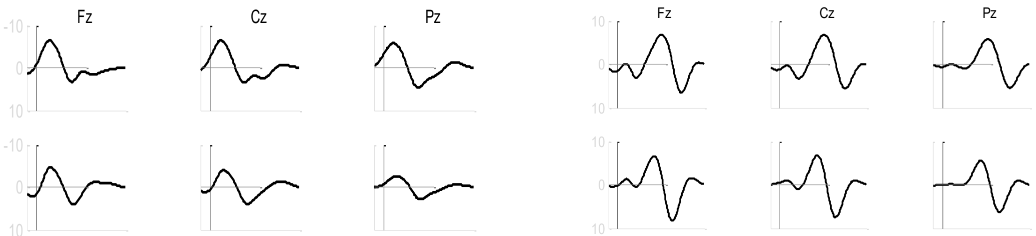
2 Methods

68 students without pathologies of sensory and central nervous systems were tested. All participants signed a voluntary agreement to participate in the research. We used paradigm of successive sensory stimulation of different significance (first - ignored stimulus, second - target stimulus, then vice versa) and modality (auditory and visual). Target auditory stimuli were presented with a frequency of 1 and 1.2 kHz, an intensity of 60 dB or visual flashes were presented with 9 kD of brightness and duration of 0.01 sec; with probability 0.15; 0.5 and 0.85. Task composition: as a response to the target stimuli, it is necessary to press to the mouse button to corresponding sensor stimulus. The ignored stimulus without a response in the auditory modality was presented with a frequency of 1.1 kHz, an intensity

of 90 dB; visual - 9 kD. The visual ignored stimulus was presented as three non-interval flashes. The intervals between target and ignored successive stimuli were 0.3 sec. For EEG and time reaction recoding, sensory stimulations we used a computer encephalograph-analyzer "Encephalan-131-03" (Taganrog, Russia). Adaptive EEG filtering we used in response to target or ignored stimuli. The frequency band filtration of the brain oscillations was 0.5-3 Hz for delta, 4-7 Hz for theta, 8-13 Hz for alpha band. We used MATLAB to mathematic and statistical analysis of the EEG and ERP dates.

3 Results

Adaptive filtering of delta, theta, and alpha bands of brain activity makes it possible to estimate the ratio of these oscillations during the analysis of successive stimuli presentation for target and ignored different modalities. We showed that the differentiation of target stimuli is associated with an increase in the delta oscillation (Fig. 1) and theta pattern decrease, independently of the modality and significant of the stimulus.

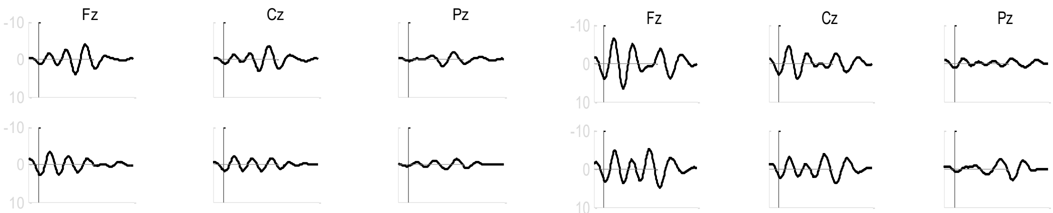


A (first - target stimulus, second – ignored) B (first - ignores second, target stimulus)

Fig. 1. Evoked delta wave during successive sensory stimulation

The delta wave covers the contingent negative expectation wave of the target stimulus, the mismatch negativity and the P300 ERP component. Localization of the negative and positive half-period of the delta wave is observed in the central parietal areas. A decrease of the probability of target stimuli leads to delta wave increase. We showed that the ERP delta band is highly correlated with 2 Hz induced oscillator.

The perception of the ignored stimulus (Fig. 2) is associated with desynchronization of the delta band oscillation and with the dominance of the evoked theta pattern, independent to modality stimulus or theirs order to presentation (the target or ignored stimuli). Evoked theta pattern controls the development of the N1, N2, P2 components ERP. The theta focus is localized in the frontal-central areas. Theta pattern corresponds to the oscillator with frequency of 5-6 Hz.



A (first - target stimulus, second – ignored) B (first - ignores second, target stimulus)

Fig. 2. Evoked theta wave during successive sensory stimulation

Evoked alpha pattern of brain oscillation under conditions of unimodal auditory successive stimulus was not found. We observed that two foci of alfa pattern in the conditions of cross-modal successive stimulation. The frontal evoked alpha focus was developed in response to the ignored stimulus independent to modality. The parietal-occipital evoked alpha focus was developed in response to a visual target stimulus and was found at a frequency of 9-10 Hz.

4 Discussion

Our data showed that the target stimuli analysis associated with an increase of evoked delta oscillation and the decrease of evoked theta pattern of brain in condition perception of ignored stimulus. The delta wave corresponds to the different stage of perception such as waiting, mismatch negativity components and the P3b component ERP, independently on the modality or the order of the stimulus. Evoked delta wave focus is localized in the central-parietal brain areas.

The literature data contain confirms of the role of the evoked delta wave as an enhancement of sensory signals and an enhancement of the wakefulness and attention paradigm [10]. In addition, the modulation role of the delta wave was shown also. Thus, slow cortical oscillations are involved in the process of grouping other high-frequency cerebral rhythms through the cortico-cortical and corticothalamic pathways [10]. It has also been shown that the phase-reset of the low-frequency delta oscillation in response to a warning stimulus occurs to prepare attention for the analysis of a follow significant stimulus. This process is based on the return of inhibition mechanism [40].

In our opinion, the development of a positive half-period of evoked delta wave in response to the ignored stimulus is associated with the processes of suppressed this stimulus, as well as the decrease in sensitivity thresholds and preparation of the attention system to follow target stimulus analysis. The positive half-period of the evoked delta wave to the target stimulus coordinates the development of the waiting stage and the mismatch negativity to the target stimulus. This delta wave is similar to the envelope of a low-frequency modulator. Also, the positive period of the delta wave coincides with the development of the P3b component ERP to target stimulus.

We showed that the perception of the ignored stimulus is associated with desynchronization of the evoked delta oscillation and with the dominance of the evoked theta pattern of ERP, impudently to the modality and successive of the stimulus. Evoked theta pattern controls the development of the N1, N2, P2 ERP components, and these foci were localized in the frontal-central areas.

Exogenously induced synchronization of theta rhythms in fronto-parietal areas is associated with visual perception and attention [16], working memory, and the efficiency of sensorimotor response [17], as well as with the processes of recognition, detection, short-term retention and planning [18, 19].

We supposed that the increasing of the evoked theta pattern is due to the N1, P2, N2 and P3a ERP components development, its role is associated with the analysis of the physical parameters of the stimulus, which is the correspond to research [8]. The evoked theta pattern could participate to the main stages of perception: detection (N1), discrimination and decision-making (N2), as well as reflecting a deficit in the ability to withdraw attentional resources from stimuli (P2), analysis of the novelty and significance of the stimulus (P3a). The increasing of evoked theta pattern is due to the ignored stimulus, which reflects the processes of active inhibition and memory involvement.

The alpha pattern of evoked activity was observed in our studies in two foci of activity: frontal and parietal-occipital areas. Frontal focus alpha pattern was formed as response to an ignored stimulus, parietal-occipital as response to of target stimulus.

It is known that alpha patterns are associated with modulations of sensory and cognitive ERP components [22, 23, 41, 42]. It was shown that the evoked alpha pattern is involved in the suppression of insignificant information, limiting the flows of information, which is confirmed by our data. Evoked alpha patterns are necessary for the alternation of rapid changes in the state of attention and inhibition [2, 6, 27, 28, 29, 30, 31].

Our studies have identified that fluctuations in the of the evoked alpha pattern of evoked activity (frontal and parietal-occipital foci) depend on the modality, sequence, and significance of the stimulus. According to the evoked alpha pattern is formed in multi-modal stimulation, it is possible to assume its modulation function or the organization function of intermodal sensorimotor integration by directing of attention to a significant stimulus.

Thus, the develop of a negative half-period of evoked delta wave is associated with selection to attention to the target stimulus. The positive half-period of delta oscillation is associated with desynchronization of processes and suppression to ignored stimulus. Evoked theta pattern provides the formation of the main N1, P2, N2, and P3a ERP components, and the delta wave modulates the main stages of perception: waiting, decision making, and updating the context in memory (P3 ERP) to the target stimulus. Evoked alpha oscillation is associated with processes of cross-modality sensory integration and directing attention to a significant stimulus.

We conclude that the mechanism of unimodal successive analysis of stimuli of different significance (target and ignored) is associated with the dynamics of excitability (refractoriness) within the sensory channel. In conditions of a multimodal successive it is associated with mechanisms of co-activation parallel processing and specific intersensory integration.

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