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The Ratio between the Phasic and Tonic Components of the Frontal Midline Θ Rhythm in the Attention Test

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Abstract—The frontal midline Θ rhythm in the *GO*/*NOGO* paradigm was studied in a group of apparently healthy children at ages of 7–13 years. Calculated event-related synchronization in response to stimulus presentation in tests was used as an index of the phasic component, and the relative change in the EEG power in the Θ band (compared to the activity in the state of quiet wakefulness) in response to test performance was used as an index of the tonic component. Subjects were divided into two groups according to the characteristics of the baseline Θ activity. A statistically significant correlation between the phasic and tonic components of the Θ rhythm was found in the group of children characterized by the absence of the frontal midline Θ rhythm in the baseline EEG. No such correlation was found in the group of children characterized by a pronounced baseline Θ rhythm. The results testify to the functional heterogeneity of the phasic and tonic components of the human midline Θ rhythm.

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INTRODUCTION

The frontal midline Θ rhythm was originally described in the early 1950s [1, 2]. This rhythm is observed both in the state of quiet wakefulness and during sleep [3]. It increases during the performance of tests actively involving working memory [4–6]. The maximum of this rhythm is recorded in the *Fz* lead (international 10–20 system), and its frequency varies in different subjects from 5 to 7.5 Hz.

Studies with low-resolution electromagnetic tomography (LORETA) and location of dipole sources point to the involvement of the anterior cingulate gyrus in the generation of this rhythm [7, 8]. This location of the area of generation of this rhythm suggests a relationship of the frontal midline Θ rhythm with the activity of the brain limbic system. Normally, in the state of quiet wakefulness, this rhythm is clearly observed in 40% of young adult subjects as short (less than 1 s) bursts [9].

The purpose of our work was to study the tonic (not associated with stimuli) and phasic (synchronous with stimulus presentation) components of EEG responses in the Θ band in healthy children in the state of quiet wakefulness and during the performance of attention tests.

EXPERIMENTAL

A group of 81 apparently healthy children (46 boys and 35 girls) at ages from 7 to 13 years was selected for the study. The state of health of the children was assessed on the basis of a questionnaire filled out by their parents. Children without chronic diseases, not taking medicines, and with good or excellent academic performance were selected.

During the examination, the subjects were in an electrically shielded room in a semisupine position in a comfortable armchair at a distance of 1 m from a monitor and loudspeakers.

The EEG was recorded with a 24-channel digital electroencephalograph (OOO Mitsar, Russia), an electrode cap (ElectroCap, United States), and the WinEEG 1.5 software package (V.A. Ponomarev, Institute of the Human Brain, St. Petersburg, Russia). Nineteen Ag/AgCl electrodes were arranged on the head surface according to the international 10–20 system in leads Fp_1; Fp_2; F_7; F_3; Fz; F_4; F_8; T_3; C_3; Cz; T_4; T_5; P_3; Pz; P_4; T_6; O_1, and O_2. Reference electrodes were placed on the earlobes, and the ground electrode was located in the *Fpz* lead. The electrode impedance did not exceed 5kΩ. To control the accuracy of test performance and to measure the response time, we recorded a signal triggered by pressing a button. The EEG sampling rate was 250 Hz. The parameters of high- and low-pass filters were 0.3 and 30 Hz, respectively; a rejector filter (50 Hz) was also used.

A monopolar montage (the weighted average reference according to Lemos) was used in this work. This montage uses a weighted mean reference potential equal to the sum of neighboring electrode potentials (relative to the reference) multiplied by standard coefficients (the coefficient of the original electrode being equal to unity, and coefficients for distant electrodes being small). The use of this montage reduces the influence of the common reference on initial EEG signals and localizes the EEG signal and possible artifacts to the specific channels where the signal or artifacts are recorded. The coefficients for the montage calculation were taken from [10].

We used the method of spatial filtration for elimination of eye movement artifacts. The spatial filter of eye movement artifacts was found by the method of independent components [11].

For the calculation of spectra and event-related desynchronization, the EEG fragments with slow waves (in the frequency band 0–1 Hz with an amplitude of 50 μV or higher) and fast oscillations (in the band 20–35 Hz with an amplitude of 35 μV or higher) were automatically removed.

We used a two-stimulus modification of tests employing the *GO*/*NOGO* paradigm. The test consisted of 400 trials. Pictures of animals, plants, and humans (20 different pictures for each stimulus type) were used as stimuli. Pairs of visual stimuli made up trials: animal–animal (a *GO* trial), animal–plant (a *NOGO* trial), plant–plant (an *Ignore* trial), and plant–human (a *Novel* trial). Trials were presented in a pseudorandom order with a probability of 25%.

The trial duration was 3000 ms, each stimulus duration was 100 ms, the duration of the interval between two stimuli in a pair was 1100 ms, and the interval between pairs of stimuli was 2000 ms. The subjects had to press the button as fast and accurately as possible in response to the animal–animal pair but not to press the button in response to presentations of other trials.

The EEG was recorded for 3 min in the state of quiet wakefulness with the eyes open (the baseline EEG).

Power spectra were analyzed. The spectra were calculated for 4-s epochs with 50% overlap. Prior to the calculation, the EEG was smoothed with the use of the Hanning time window. The spectra were calculated using the fast Fourier transform.

An increase in the EEG Θ rhythm in the *Fz* lead is reflected in a power spectrum peak. The EEG spectral power in the low-frequency band decreased with age (Fig. 1a). To assess the power of the rhythmic component of the Θ activity, the integral of the spectrum curve in the band 5.5–7.5 Hz was calculated by the method of trapezoids and the area of the trapezoid with vertices corresponding to the border points of the frequency band was subtracted. As a result, the area of the Θ-rhythm peak as such was obtained (Fig. 1b). This parameter is referred to as *d*Θ hereinafter. This parameter does not depend on the change in the level of the spectral power with age because it is counted off from this level.

The event-related synchronization (ERS) was calculated by the method of Pfurtsheller [12] in the following way. (1) Bandpass filtering was performed in the band 5.5–7.5 Hz. (2) For reducing the effects of the harmonics of the evoked potential components on the ERS, the averaged evoked potentials were subtracted from the initial EEG. (3) The values of each digital EEG reading were squared and averaged over the set of trials to estimate the dynamic changes in the EEG signal power in the given frequency band. (4) For the reduction of data variance, the obtained pattern of EEG power changes was smoothed by the method of the moving mean with an averaging epoch width of 100 ms. (5) The ERS was calculated as the percent change in the signal power at each time point with respect to the mean power in the prestimulus interval (*R*) by the formula

$$ERS = ((P(i) - R)/R) \times 100.$$

Then, the obtained signals were averaged over the pairs of visual stimuli for conditions *a–a* (*GO*, both stimuli are pictures of animals), *a–p* (*NOGO*, the first stimulus is an animal, and the second stimulus is a plant), "+" (*GO* and *NOGO*, the first stimulus is an animal), and "–" (*p–p* and *p–h*, *NOGO*, the first stimulus is a plant).

The number of omissions of relevant (*GO* trials) pairs of stimuli (inattention errors) and the number of erroneous responses to irrelevant stimulus pairs (*NOGO* trials) (errors associated with impulsiveness) were calculated for each subject. For measuring the rate of sensory and cognitive processes, the mean reaction time was calculated (for correct responses to a *G*O trial).

RESULTS

Amplitude spectra. The EEG amplitude spectrum in the *Fz* lead calculated in the state of quiet wakefulness with the eyes open (the baseline EEG) averaged for all subjects is presented in Fig. 1c. As can be seen from the figure, there is a slightly pronounced spectral peak in the band 5.5–7.5 Hz. The topogram at the moment of the maximum of this peak suggests a frontocentral distribution of this activity. The given peak (*d*Θ, see Methods) characterizes the baseline frontal midline Θ rhythm in the group of healthy subjects. For brevity, we will also refer to it as the Θ rhythm hereinafter.

The distribution of the Θ-rhythm amplitude over all the subjects is presented in Fig. 1c. It can be seen in the figure that the distribution is shifted towards positive values. At the same time, a rather high percent of subjects did not display a distinct peak of the Θ rhythm in spectrograms; i.e., for these subjects, the *d*Θ values are less than zero. Thus, it is reasonable to divide the subjects into two groups: (1) subjects with the Θ rhythm in the baseline EEG (with *d*Θ values above the mean value for the total sample) and (2) subjects without the Θ rhythm in the baseline EEG (with *d*Θ values below the mean value for the total sample).

The performance of the *GO*/*NOGO* test by the subjects led to a marked increase in the Θ rhythm per se and the activity in the Θ and Δ bands (Figs. 1d, 1e, the left curves). The band of the Θ activity in these cases

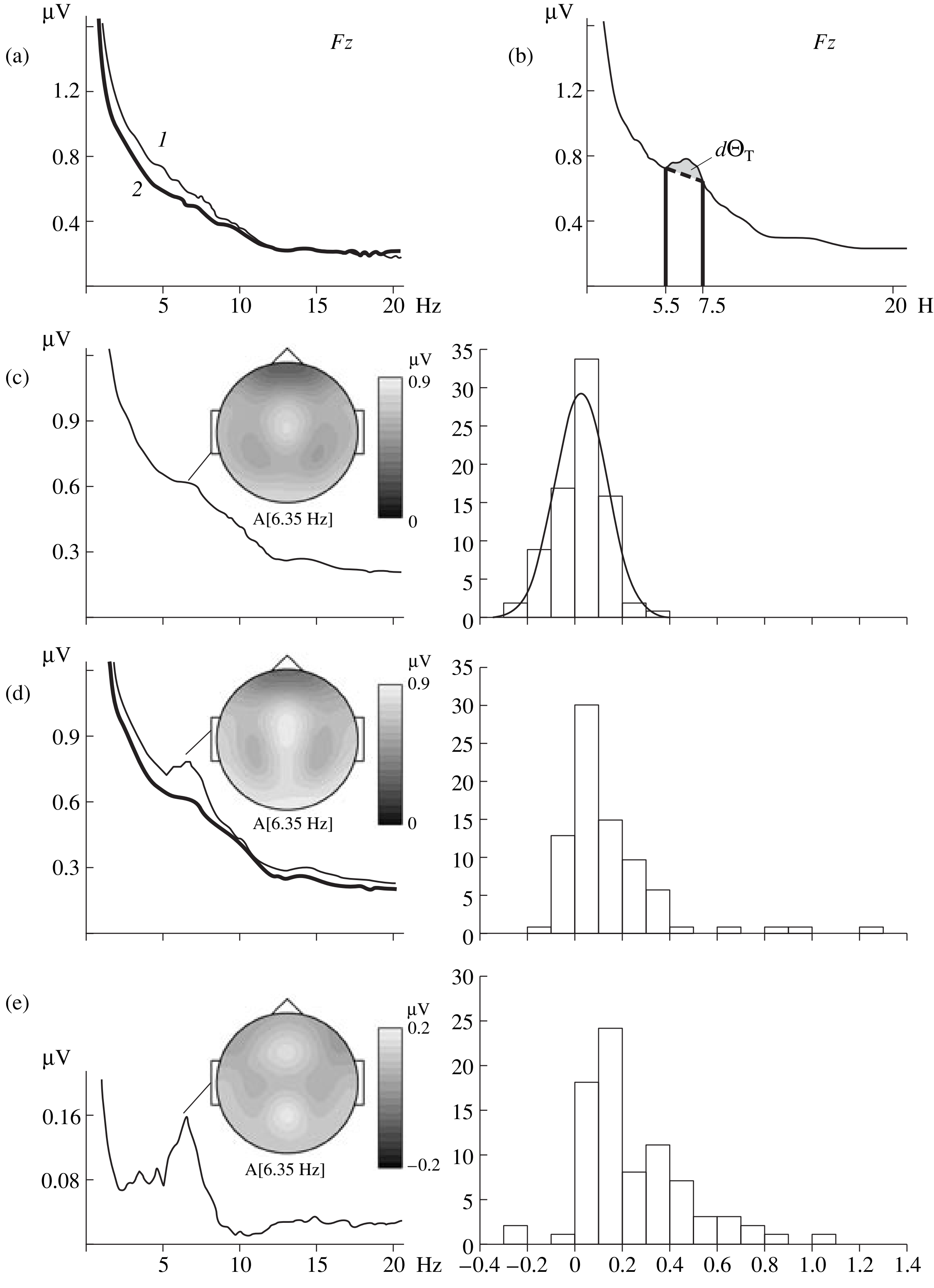

Fig. 1. Changes in the EEG spectra with age and during the performance of the attention test. (a) Amplitude spectra in the *Fz* lead in the state of quiet wakefulness in (*1*) a group of 8- to 9-year-old children (19 subjects) and (*2*) a group of 12- to 13-year-old children (23 subjects). (b) Calculation of the Θ-rhythm amplitude $d\Theta_T$ in the frequency band 5.5–7.5 Hz. (c) The amplitude spectrum, topogram, and distribution of the amplitude of the midline Θ rhythm for all subjects in the state of quiet wakefulness. (d) The amplitude spectrum, topogram, and distribution of the amplitude of the midline Θ rhythm for all subjects during the attention test performance (the spectrum in the state of quiet wakefulness (thick line) is given for comparison). (e) The difference spectrum (test—baseline), topogram, and amplitude distribution of the midline Θ rhythm.

was substantially broader than the band of the frontal Θ rhythm per se in the *Fz* lead (3–8 Hz). In other words, the amplitude of not only the Θ rhythm, but also the Θ activity in a broader frequency band, increased.

The distribution of the Θ-rhythm amplitudes is presented in Fig. 1d (the right diagram). It is shifted (as compared to the baseline) towards positive values, and the distribution of amplitude differences (the Θ-rhythm amplitude in the baseline fragment is subtracted from the Θ-rhythm amplitude corresponding to the test performance) has the form of a lognormal distribution (Fig. 1e).

The ratio between the tonic and phasic components of the Θ activity. The tonic component of the Θ rhythm during the test performance can be estimated as the difference between the EEG amplitude in the Θ band during the test performance (Θ_T) and in the state of quiet wakefulness (baseline) (Θ_B). The scatterplot of the logarithm in the Θ rhythm of the test-produced change (ordinate, $\log[\Theta_T - \Theta_B]$) against the baseline Θ-rhythm amplitude (abscissa, $d\Theta_B$) is presented in Fig. 2a. The correlation between these values is not statistically significant ($r = 0.18$, $p = 0.122$).

The phasic component of the Θ rhythm during the test performance was estimated with the averaged (over all stimuli) index of the ERS in the Θ band. The scatterplot of this index (ordinate) and the logarithm of the relative increase in this rhythm during the test performance ($\log[(\Theta_T - \Theta_B)/\Theta_B]$) is presented in Fig. 2b. The logarithms were taken for standardization of the distribution. Though the correlation between the parameters under study is statistically significant ($p < 0.03$), the correlation coefficient is relatively small ($r = 0.25$).

Similar scatterplots calculated for the two groups of subjects are shown in Fig. 3 (the left and right plots). A significant ($p < 0.01$) and relatively high ($r = 0.44$) correlation was found between the tonic and phasic components of the Θ rhythm for the group of subjects without a prominent Θ rhythm in the baseline EEG. However, there was no correlation between the tonic and phasic components ($p < 0.55$, $r = 0.11$) in the group of subjects with a Θ rhythm in the baseline EEG. In both groups, the ERS is negatively correlated with the time of response to *GO* stimuli.

DISCUSSION

The Θ rhythm in the state of quiet wakefulness. The history of studies of the frontal midline Θ rhythm is intricate. For a long time, the existence of this rhythm was not acknowledged by scientific society [13]. This is explained by the fact that, normally, the human Θ rhythm appears occasionally at intervals of several tens of seconds in the form of short (less than 1 s) bursts. This phenomenon is fundamentally different from the hippocampal Θ rhythm observed in animals. In animals, especially rodents, the Θ rhythm is observed as long-term continuous oscillations. Moreover, this rhythm is recorded in only one third of adult subjects in the state of quiet wakefulness. It is clear that, during visual analysis, it is easy to miss such short-term bursts of Θ activity, which can be seen only in the frontal leads. Only the large-scale use of spectral analysis brought about qualitative changes in the study of the frontal midline Θ rhythm. This rhythm is revealed in the spectrum curves of the *Fz* lead as a peak in the band 5.5–7.5 Hz.

It should be emphasized that, in the EEG, the Θ rhythm manifests itself against the background of irregular activity in the Θ band. In the amplitude spectra, this activity has the shape of a power function. To a first approximation, this function in the interval 5.5–7.5 Hz may be approximated by a straight line. It is natural to assume that the area above this line will correspond to the Θ-rhythm power. This is why the first step in our study was to isolate the power of the Θ *rhythm* per se from the Θ *activity.*

It is necessary to emphasize the difference between the notions of the Θ rhythm and Θ activity. The latter notion is broader and implies any type of activity in the band 4–9 Hz. The Θ rhythm ($d\Theta$) is the Θ activity that is expressed as a peak in spectrum curves.

The peak of the Θ rhythm is barely discernible in the averaged EEG power spectra in the state of quiet wakefulness with the eyes open, and this activity in the band 5.5–7.5 Hz is distributed normally with only a slight (0.03 μV) shift towards positive values. These findings confirm the results of previous studies that showed a low occurrence of this rhythm in a healthy population and its low intensity in the quiet state [8, 13].

The Θ rhythm in the *GO/NOGO* test. The performance of the test by the subjects increased the activity in the Θ band. This phenomenon is expressed in the difference curves (test – baseline) in the form of a broad peak in the interval from 2 to 9 Hz (Fig. 3). This “broad” peak substantially differs from the “narrow” peak that characterizes the Θ rhythm during the test performance. It should be noted that the Θ rhythm in the state of quiet wakefulness was detected in only some of the subjects, whereas the increase in the broadband (2–9 Hz) Θ activity was observed in virtually all subjects. Moreover, the change in the Θ activity was observed not only in the frontal leads, but also in the parietal area, whereas the midline Θ rhythm displays an exclusively frontal distribution. All these findings suggest different physiological roles of the Θ rhythm and event-related Θ activity. This suggestion was confirmed by further analysis.

The Θ synchronization. Power spectra calculated for a certain period of analysis give a general idea of the tonic component of the Θ activity in the corresponding time interval. An idea of the phasic component of the Θ activity, i.e., the Θ rhythm induced by the stimulus presentation, is given by the ERS curves. Like the difference spectrum curves, the ERS curves distinctly show two spatial areas that generate phasic Θ activity

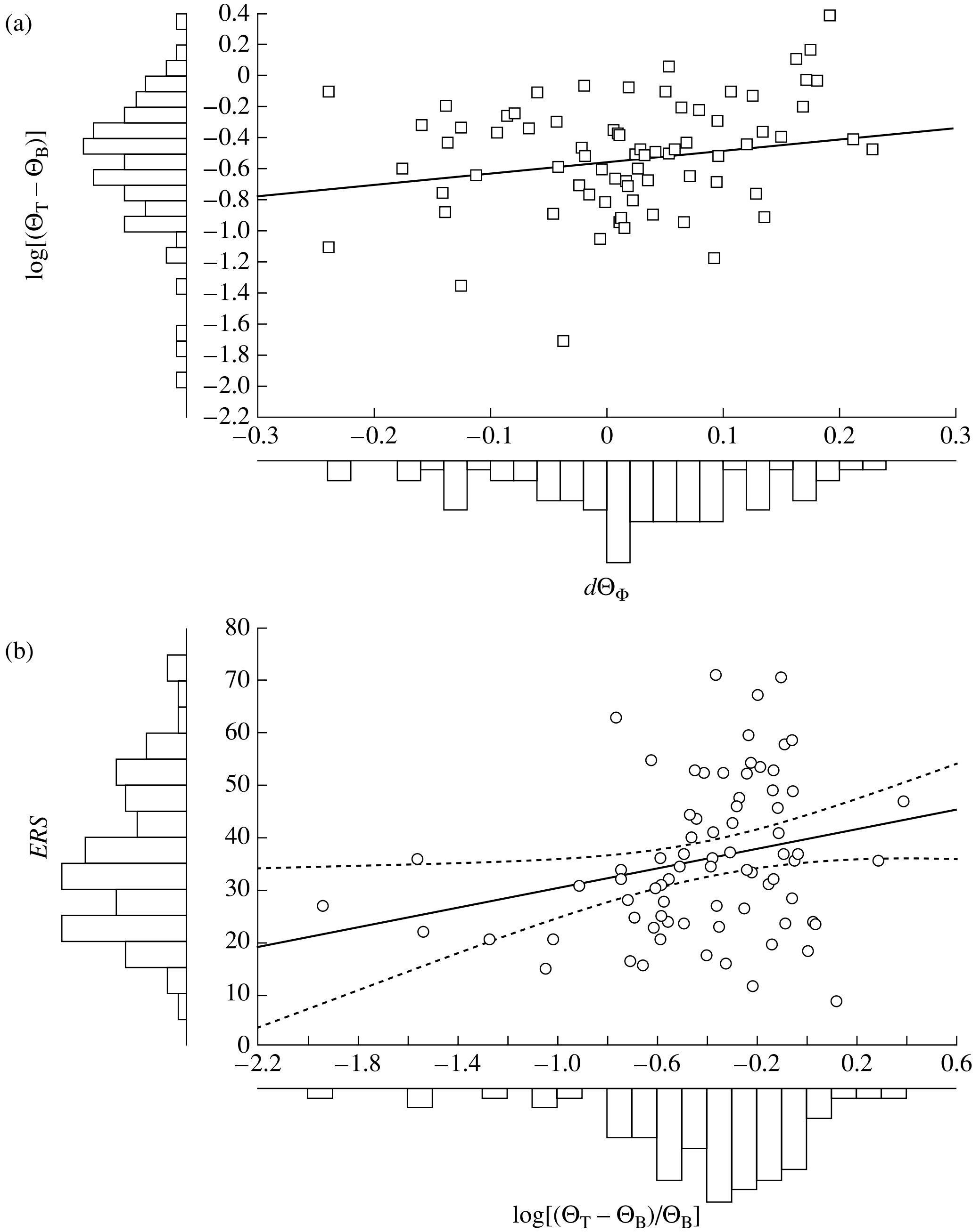

Fig. 2. Scatterplots of the phasic and tonic components of the Θ rhythm. (a) Abscissa: the amplitude $d\Theta_B$ of the Θ rhythm in the state of quiet wakefulness (baseline); ordinate: test-induced changes in the Θ rhythm on a logarithmic scale. (b) Abscissa: relative changes in the Θ rhythm during the test performance on a logarithmic scale; ordinate: ERS in response to stimulus presentation.

(Fig. 3). These areas correspond to the frontal and parietal cortices. The results agree with the observations of Θ-rhythm changes recorded with the use of implanted electrodes in epileptic patients [14]. These studies demonstrated an increase in the Θ activity associated with periods of information fixation in the working memory. This phenomenon was termed Θ gating. For our discussion, it is important that the electrodes recording this activity were in both the frontal and parietal areas.

The ratio between the tonic and phasic components of the Θ activity. Thus, the Θ rhythm and the test-induced Θ activity differ both in the frequency band (a narrow band of the Θ rhythm and a broad band of the Θ activity) and in the spatial distribution (the Θ rhythm has a maximum only in the frontal lead, while the Θ activity is recorded in the frontoparietal leads). If the Θ rhythm is absent in the baseline EEG, the changes in the EEG spectral density in the Θ band are distinctly correlated with the Θ ERS (Fig. 3, the left

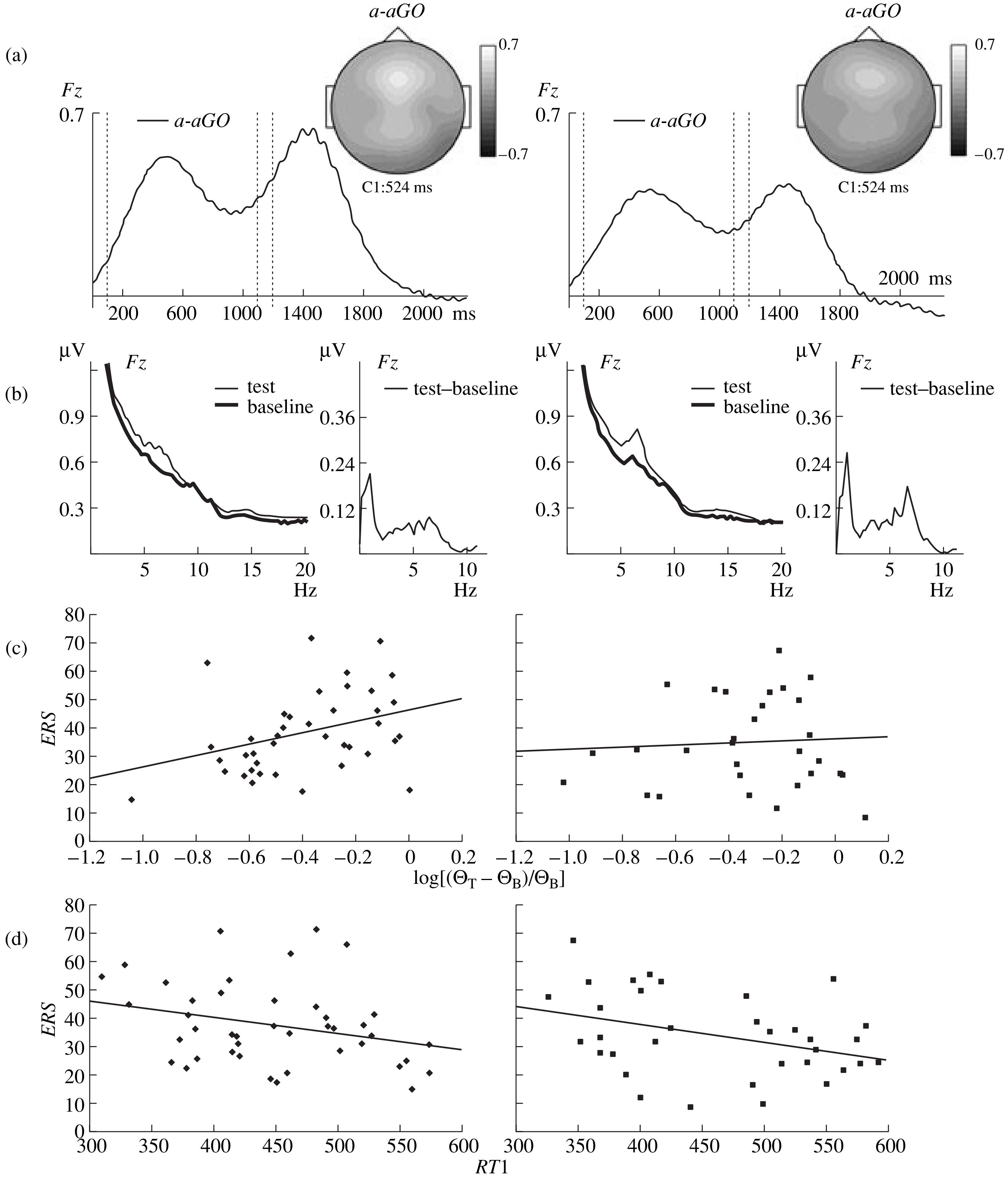

Fig. 3. ERS and changes in the Θ rhythm caused by the attention test performance in two groups of subjects: the group without the frontal midline Θ rhythm in the baseline EEG (the left curve) and the group with the frontal midline Θ rhythm (the right curve). (a) ERS in response to *GO* stimuli. Ordinate: ERS; abscissa: time. Topograms of the ERS at the maximum point (524 ms after the first stimulus presentation) are shown at the top right. (b) Amplitude spectra (*1*) during the test performance and (*2*) in the state of quiet wakefulness and (*3*) the difference curve. (c) Correlation of the ERS (ordinate) and the relative change in the Θ rhythm in the test (abscissa). (d) Correlation of the Θ synchronization and the reaction time to *GO* stimuli.

curves). If the Θ rhythm is recorded in the baseline EEG, this rhythm is not synchronized with the moments of stimulus presentation, which is reflected in the disappearance of the correlation (Fig. 3, the right curves). Note that the Θ synchronization is correlated with behavior: the higher the synchronization, the faster the test performance. This correlation with the speed of cognitive processes suggests a relationship of the Θ synchronization with attention.

The nature of the Θ rhythm. Obviously, the EEG activity in the Θ band is a heterogeneous phenomenon. First, one should discriminate between the rhythmic component of the Θ activity (the Θ rhythm per se) observed as a sharp peak in spectrograms and the Θ activity represented in spectrograms in the form of a broad peak. Second, the changes in the rhythmic component are not synchronized with the moments of stimulus presentation and can be considered to be tonic components. On the contrary, changes in the Θ activity are evoked by stimuli and are phasic components.

Thus, regarding the nature of the Θ activity, one should bear in mind its heterogeneity. It is thought that, in lower animals, the Θ rhythm is related to the hippocampus. It is distinctly pronounced and appears or disappears depending on the animal's behavior. The presence of the Θ rhythm facilitates posttetanic potentiation and, presumably, supports the consolidation of memory [15]. All fundamental works concerning the origin of the Θ rhythm and its role in memory consolidation were performed with the use of rats. In higher animals and humans, the Θ rhythm in the hippocampus is not dominant and appears in the form of short bursts. No direct relationship between the hippocampal Θ rhythm in rats and the bursts of the Θ rhythm in humans has been proved, and their similar functional roles can only be suggested.

CONCLUSIONS

(1) A peak in the band 5.5–7.5 Hz corresponding to the frontal midline Θ rhythm is observed in the EEG amplitude spectra of the frontal leads in approximately half of healthy subjects at ages from 7 to 13 years in the state of quiet wakefulness.

(2) In all subjects, the performance of an attention test leads to an increase in the amplitude of the Θ rhythm and synchronization of the Θ rhythm with presented stimuli.

(3) A statistically significant correlation between the phasic and tonic components of the Θ rhythm was found in the group of children displaying no frontal Θ rhythm in the baseline EEG, whereas no such correlation was found in the group of children characterized by the presence of a distinct baseline peak of the Θ rhythm.

(4) The results testify to the functional heterogeneity of the mechanisms of generation of the human midline Θ rhythm during the performance of attention tests.

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REFERENCES

1. Mundy-Castle, A.C., Theta and Beta Rhythm in the Electroencephalograms of Normal Adults, *Electroencephalogr. Clin. Neurophysiol.*, 1951, vol. 3, p. 477.
2. Brazier, M.A.B. and Casby, J.U., Crosscorrelation and Autocorrelation Studies of Electroencephalographic Potentials, *Electroencephalogr. Clin. Neurophysiol.*, 1952, vol. 4, p. 201.
3. Hayashi, H., Iijima, S., Sugita, Y., et al., Appearance of Frontal Mid-line Theta Rhythm during Sleep and Its Relation to Mental Activity, *Electroencephalogr. Clin. Neurophysiol.*, 1987, vol. 66, p. 66.
4. Inanaga, K., Frontal Midline Theta Rhythm and Mental Activity, *Psychiatry Clin. Neurosci.*, 1998, vol. 52, no. 6, p. 555.
5. Jensen, O. and Tesche, C.D., Frontal Theta Activity in Humans Increases with Memory Load in a Working Memory Task, *Eur. J. Neurosci.*, 2002, vol. 15, p. 1395.
6. Klimesch, W., EEG Alpha and Theta Oscillations Reflect Cognitive and Memory Performance: A Review and Analysis, *Brain Res. Rev.*, 1999, vol. 29, p. 169.
7. Gevins, A., Smith, M.E., McEvoy, L., and Yu, D., High-Resolution EEG Mapping of Cortical Activation Related to Working Memory: Effects of Task Difficulty, Type of Processing, and Practice, *Cerebr. Cort.*, 1997, vol. 7, p. 374.
8. Asada, H., Fukuda, Y., Tsunoda, S., et al., Frontal Midline Theta Rhythms Reflect Alternative Activation of Prefrontal Cortex and Anterior Cingulate Cortex in Humans, *Neurosci. Lett.*, 1999, vol. 274, p. 29.
9. Yamaguchi, Y. and Ishihara, T., Evaluation of Frontal Midline Theta Rhythm in Association with Intellectual Functions, *Neurosciences*, 1990, vol. 16, p. 582.
10. Lemos, M.S. and Fisch, B.J., The Weighted Average Reference Montage, *Electroencephalogr. Clin. Neurophysiol.*, 1991, vol. 79, no. 5, p. 36.
11. Ille, N., Berg, P., and Scherg, M., Artifact Correction of the Ongoing EEG Using Spatial Filters Based on Artifact and Brain Signal Topographies, *J. Clin. Neurophysiol.*, 2002, vol. 19, no. 2, p. 113.
12. Kalcher, J. and Pfurtscheller, G., Doscrimination between Phase-Locked and Non-Phase-Locked Event-Related EEG Activity, *Electroencephalogr. Clin. Neurophysiol.*, 1995, vol. 94, p. 381.
13. Niedermeyer, E., The Normal EEG of the Waking Adult, *Electroencephalography*, Niedermeyer, E., Ed., Williams and Wilkins, 1993, 4th edition, pp. 131–152.
14. Raghavachari, S., Kahana, M., Rizzuto, D.S., et al., Gating of Human Theta Oscillations by a Working Memory Task, *J. Neurosci.*, 2001, vol. 21, no. 9, p. 3175.
15. Vinogradova, O.S., *Gippokamp i pamyat'* (The Hippocampus and Memory), Moscow: Nauka, 1975.