Probability Patterns of the Human EEG Narrow-Band Differential Spectra during Memory Processes

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Abstract—The EEG correlates of the stages of short-term memorizing and retention of the actual (during exposure) and perceptive (after exposure) visual matrix representations were studied. The task suggested no verbal or semantic interpretation and required no motor response. A narrow-band spectral analysis of the data combined with a probabilistic approach showed that, in 50-80% of trials, the processing of actual and perceptive images was accompanied by an increase in 6- and a decrease in a-P-activity within the wide frequency bands of 3.5-7 and 8.5-22 Hz, respectively. These EEG effects revealed no noticeable interhemispheric asymmetry, though their manifestations were weakened along the direction from the occipital to the frontal regions. The lowering of memory load without the attenuation of attention processes slightly decreased the EEG effects within the a-P band and completely eliminated them in the 0 band. The problem of searching for the EEG correlates of invariant components of cognitive activity in man is discussed.

In recent years, considerable attention has been focused on the generalized cortical phenomena of EEG desynchronization-synchronization as the functional markers of cerebral activation-deactivation accompanying cognitive activity in man [1-3]. The regional and frequency specificity of these phenomena is a problem of primary importance for the interpretation of experimental data. However, in most studies, the spatial characteristics of EEG phenomena (an event-related desynchronization, for instance) were shown to reflect either the modal specificity of stimuli and the possibility of their semantic interpretation or direct verbalization, or the character of the task-related motor component of cognitive activity. The data of this kind do not help to reveal the EEG components of invariant cognitive processes, such as attention and memory. Therefore, it would be interesting to study the EEG correlates of human cognitive activity with nonverbalized stimuli, which could be presented in an actual and perceptive mode and would not require any motor responses.

As for the analysis of frequency-specific EEG transformations in cognitive tasks, the most popular approach has been the conventional calculation of an average spectral power for a sufficiently wide frequency band [4]. This approach is justified not only by the resulting compact representation of spectral characteristics, but also by the necessity of applying a smoothing procedure to obtain statistically stable parameters from relatively short EEG fragments.

At the same time, factor analysis of the narrow-band EEG spectra [5-7] have indicated that various spectral bands can be grouped in a sufficiently complex and dynamic way, which is far from the traditional scheme of linear frequency distribution from delta to gamma-bands. A detailed frequency analysis of the EEG has shown that, within the limits of classical frequency ranges, such as an oc-band, several narrow-band ranges with different dynamic properties [8-11] and spatial relations [12, 13] can be distinguished. These authors suggested that it is precisely the functional heterogeneity within the EEG a-band that can explain the discrepancy in its assessments during different cognitive tasks.

When a semantic complexity of stimuli commonly used in cognitive experiments are taken into account, it becomes apparent that the assessment of EEG rhythms within the wide spectral bands not only masks a native dynamics of possible narrow-band EEG correlates of the cognitive activity, but also gives rise to ambiguous data interpretation.

Therefore, this study was aimed at investigating the EEG correlates of some invariant processes of cognitive activity using the narrow-band spectral analysis and tasks, which imply no semantic interpretation of stimuli and no preparatory setting for motor response.

METHODS

The study involved 18 volunteers, healthy Moscow students from the ages of 19 to 26 years. All the subjects were preliminarily informed about the character of the forthcoming experiments. Only the subjects with normal autonomic (blood pressure and pulse rate) and psychometric (Eysenck's, Spielberg-Khanin's and Doskin's scales) indices were selected for further examination. All EEGs were recorded in the morning, before lunchtime.

1. Basic testing. The visual stimuli presented for memorizing were nonverbalizable matrices composed of nine square elements (1.5 x 1.5 cm^2) presented on a matrix screen 6 x 6 elements in size, which was posi-

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tioned 60 to 70 cm away from the subject's eyes. Each element was covered by a semitransparent metal plating electrically isolated from all the other elements of the screen and connected with a block scoring the task performance. The combination of elements was selected quasi-randomly and presented on the screen for 20 s by lighting with the bottom-mounted red light diodes. Over the course of the experiment, the illumination in the laboratory box was held constant on such a level that allowed the subject to reliably distinguish the matrix elements without lighting. The technique of matrix visual testing was described earlier in more detail [14].

The protocol of the experiment was as follows: immediately preceding the EEG recording, the subject was given a command "Attention to the screen" with the instruction to remember the matrix pattern to be presented. Between 30 and 50 s after the command was given, a random combination of nine matrix elements was exposed for 20 s. For the following 20 s with the lighting switched off, the subject was to sit motionless with eyes open trying to keep in mind the virtual image of the composition presented. After that, the subject was asked to reproduce the pattern: by touching the matrix elements with a special test prod. Each touch switched on the lighting of the corresponding matrix element. The EEG was recorded for 60 s before, during, and after the exposure (three periods, 20 s each). Two minutes after the reproduction was finished, a novel combination of elements was presented. A total of twelve matrix compositions were presented to each subject. Between the signal presentations, four control trials were randomly introduced. In the control trials, the EEG was also recorded, but the command "Attention to the screen" was not followed by the expected matrix presentation.

Therefore, we tested three short-term (20 s) periods: expectation, memorizing of the actual matrix image, and retention of the perceptual visual image.

2. Additional testing 1. To a separate group of five subjects inexperienced in memorizing matrix stimuli, they were presented the same way but with different instruction. They were to watch the changes in the lighting brightness of the matrix elements for 20 s and to report their number 20 s after the lighting was switched off. In fact, over the course of the experiment, the brightness was held constant.

3. Additional testing 2. Another group of five sub jects was also presented with the same stimuli, but with the instruction to look without blinking or looking aside. No report was needed in this case.

The EEGs were recorded from the occipital *(O_1* and *O_2),* parietal $(P_3$ and $P_4)$, central $(C_3$ and $C_4)$ and frontal $(F_3$ and $F_4)$ electrodes positioned by the International 10-20 system and referenced to the linked ears. The signals were amplified and filtered (0.5-30 Hz) by a Medicor electroencephalograph and digitized at a sampling rate of 128 Hz by a 12-bit analog-to-digital con-

verter. The real time EEG monitoring, filing the artifact-free fragments, and their primary treatment were performed with a specialized *CONAN* program [15].

The 2-s overlapping epochs underwent a sliding EEG spectral analysis with a step of 50 counts by means of Fast Fourier Transform using Hanning's window. Therefore, 50 individual power spectra with a 0.5 Hz step were calculated for three consecutive 20-s fragments of the 1-min EEG recordings.

Individual power spectra were logarithmically normalized and averaged over every i-th band Ml(i), M2(i), and M3(i)) within the three 20-s fragments of every EEG recording followed by computing the difference spectra [16] and evaluating the differences M2(i) - Ml(0, M3(i) - Ml(i), and M3(i) - M2(i) with Student's Mest. The difference was taken significant at $p<0.05$.

However, without smoothing within the frequency band, the spectral changes exceeding the threshold of statistical significance can strongly depend on the current combination of uncontrolled factors. The averaging of such estimates will most likely show the balance of diverse spectral changes rather than the actual "principal" process over a totality of the trials. Thereby, in addition to the conventional "energetic" estimation of the task-related EEG spectral changes, in this study, we computed the direct estimates of the relative incidence of significant spectral changes in each narrow-band range in multiple trials. To accomplish this, we calculated the probability pattern of the difference spectra (PPDS) for multiple EEG recordings from one subject and for the group of subjects as a whole. This index was calculated as the relative number of cases with significant spectral differences (with due regard for directionality of changes) for every i-th band of the EEG frequency spectrum in percentage of the total amount of the 1-min EEG recordings (Fig. 1).

RESULTS

To assess the EEG spectral changes in terms of PPDS, we should first evaluate the "stochastic background" of this index without cognitive tasks using various threshold *t* values of Student's test corresponding to the $p < 0.05$, $p < 0.01$ and $p < 0.001$ levels of significance.

Fig. 1 shows the EEG spectral differences assessed with the PPDS index at the three levels of significance. These were calculated for the right occipital lead of 12 subjects (252 1-min EEG recordings) for (1) M2(i)-Ml(i), (2) M3(i)-Ml(i), and (3) M3(i)-M2(i) pairs.

As seen from Fig. 1, none of the frequency bands in the control testing without stimulus presentation (98 recordings) demonstrated significant spectral shifts at *p*< 0.001, except for the 9-10 Hz band. Here, an increased spectral power was observed in 5-10% of cases at the second and third stages compared to the first
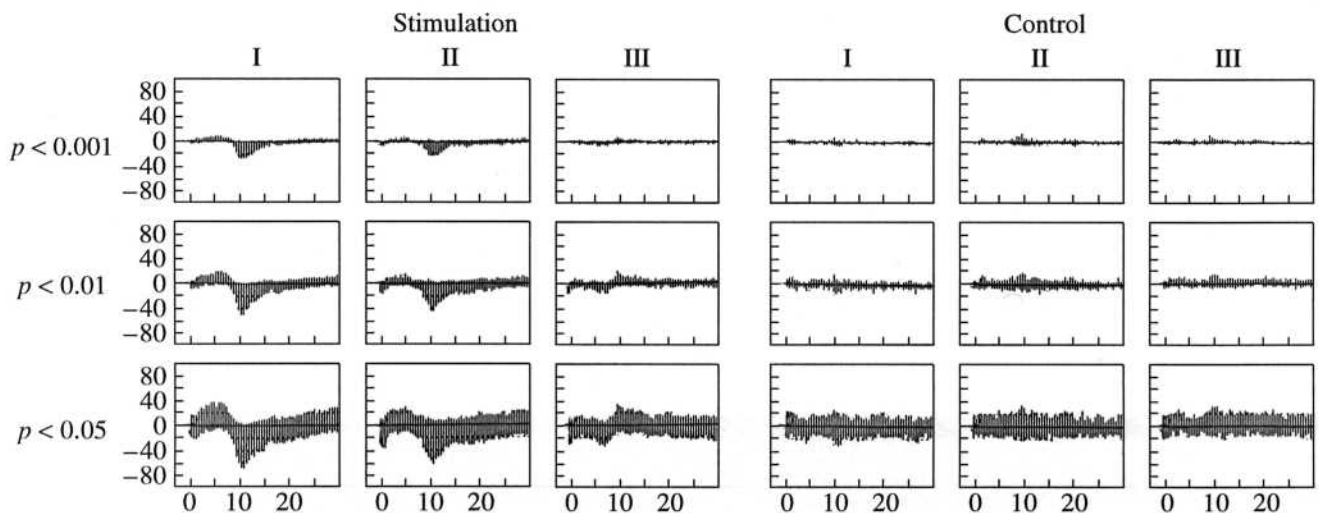
Fig. 1. Probability patterns of the narrow-band subtractive EEG spectra of the right occipital recordings revealed at various levels of significance according to Student's *t*-test for spectral differences between the consecutive stages of memory performance: "expectation" (Ml), "memorizing" (M2) and "retention" (M3) with (Stimulation) and without (Control) presentation of the visual matrix composition. The data obtained from 252 one-minute EEG recordings.

Y-axis, the incidence (%) of statistically significant changes in eachi'-th spectral band of the EEG spectrum in pairs: I. M2(i)-M 1(0; II. M3(0-M 1 (0; HI. M3(0-M2(0, where Mn(0 the average spectral power in the **i-th** band of the EEG at the N-th stage of cognitive activity. X-axis: the spectral bands with a step of 0.5 Hz selected in the range from 1.5 to 30 Hz.

one. At the same time, more than 20% of the trials with stimulus presentation showed a significant (at $p < 0.001$) power decrease in the 9-11 Hz band, while, in 10% of trials, we revealed an increased spectral power within the 3-7 Hz band. At $p < 0.01$, the corresponding values were 40 and 20%, respectively, and the opposite changes were revealed for the band of 23 Hz and higher in 10-12% of trials (Fig. 1).

For this level of significance, in control trials, the opposite changes were shown in nearly all the frequency ranges in 10-15% (for each direction). At $p < 0.05$, similar changes manifested themselves in 20% of the control trials (Fig. 1). In this case, in the 9-11 Hz band, the PPDS index displayed asymmetry in favor of the spectral power increase (by 5-10%), which was already described for the higher significance levels. Remaining qualitatively the same, the spectral changes within the 5-7 and 10-11 Hz bands at $p < 0.05$ were displayed in 40 and 60-70% of the control trials, respectively (Fig. 1).

These findings indicate that, in 15-25% of trials, even at high levels of significance $(p < 0.001)$, memorizing the visual stimulus matrix and keeping its image in memory results in the uniform changes over different EEG frequency bands not characteristic of the control trials. The significance level lowering to $p < 0.05$ sharply increased the PPDS index in the memory trials (up to 65%), being indicative of the significant variability of spectral changes still remaining uniform (unidirectional). In the control trials without visual stimulation, at $p < 0.05$, only random spectral changes could be observed, more often reaching ±20% of cases. The

PPDS value for the increased EEG activity in the narrow 9-10-Hz band revealed in 5-10% of the control trials at $p < 0.001$ did not change. This means that the random spectral shifts were characterized by high amplitudes. It is likely that these bursts in the narrow a-band, which occurred at the periods when the stimuli should be presented according to the basic experimental protocol, reflected the activation of preparatory mechanisms prior to memory test performance. In any case, an increased α-activity during short intervals between the memory and attention task possibly associated with the preparation for the next stage of performance was shown in [17].

To summarize, the $p < 0.05$ level revealed significant differences between the 20-s fragments of the 1-min EEG recordings in no more than 20% of the control trials, and these differences with equal probability could consist of an increased or decreased spectral power throughout the whole EEG frequency range,

In the memory trials, a decrease in the a-activity within the 10-12.5 Hz band was the most probable in the occipital EEG at the memorizing stage. This occurred in more than 60% of the trials. In 40% of the trials, this effect manifested itself in the wider frequency band of 9-15 Hz. Finally, in approximately 40% of the memory trials, an increased spectral power was revealed within the 0-band of 4-7 Hz. In general, the PPDS estimates exceeding the "stochastic background" that is more than 20% were characteristic of the 3-7.5 Hz (the increased power) and 8.5-23 Hz (the decreased power) bands. Analogous, though slightly less pronounced changes in the PPDS estimates were
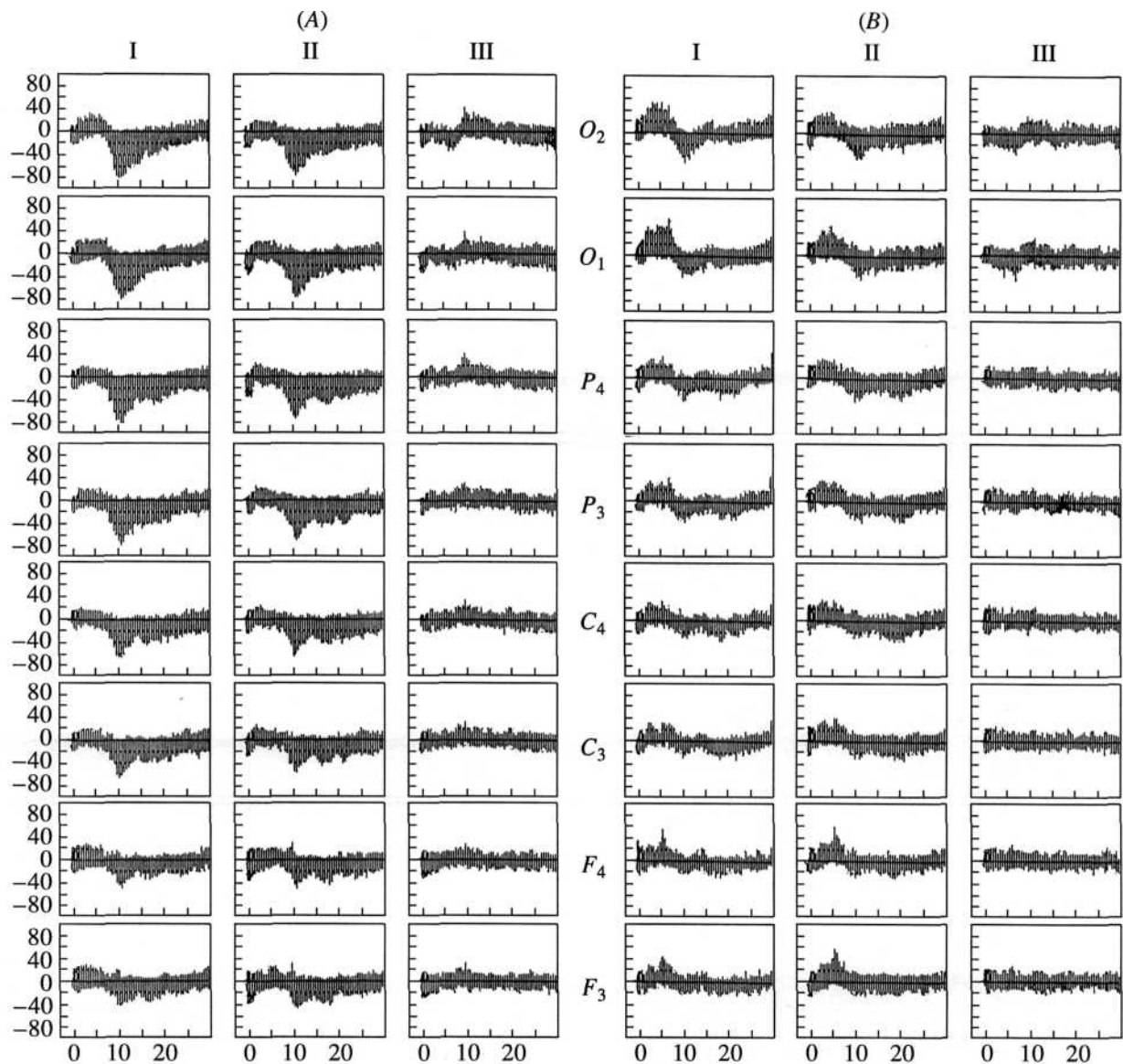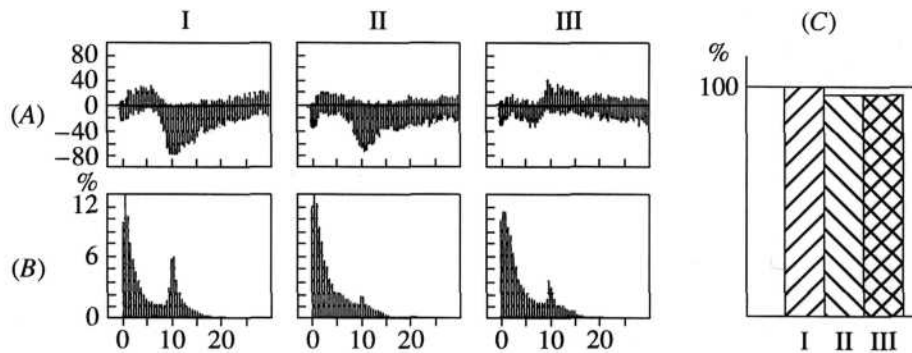
Fig. 2. Probability patterns of the narrow-band subtractive EEG spectra (at $p < 0.05$) for eight standard EEG recordings by Jasper averaged over the groups with high *(A)* 126 EEG recordings and low (B) 84 recordings a-indices. The designations as in Fig. 1.

typical of the period of visual image retention in memory (Fig. 1).

Since memory-related changes were most often observed within the oc-band, the most profound EEG frequency range, it could be assumed that the broader the dynamic amplitude range, the higher the probability of the task-related changes. To test this assumption, we divided the data into two groups depending on the level of cc-activity (Figs. *1A* and *IB)*. In fact, in the group with high cc-activity, the PPDS estimates amounted to 80% and 60% in the 10-11 and 9-14 Hz bands, respectively, remaining unaffected in the G-band (Fig. *2A)*. At the same time, in the group with low a-activity, the PPDS estimates for the 9-14 Hz frequency range were only slightly more than 25%. However, in this group, the

enhancement of 9-activity became more pronounced and occurred in 45-50% of the memory trials (Fig. *IB)*.

This relation between the PPDS index and spectral power seems to be specific for the a-band, as the PPDS values for the θ- and delta-bands were significantly lower *than* those for α-band (Flg. 3A), despite the fact that relative power for 6 was no lower than that for a wh!le, the delta-band power was even higher (Figs. *3A and 3B)*. Moreover within the cc-band itself, the relations between PPDS and spectral power were not linear, since the values of relative spectral power went down more steeply than PPDS estimates with increasing frequency *(Fig.3A)*.

Thus, the cognitive task of memorizing and short-term retention of the visual matrix stimulus, not always,

Fig. 3. Probability patterns of the narrow-band subtractive EEG spectra (A), relative spectral powers (B) and total absolute spectral power (O for the EEG recordings *(n = 126)* obtained during three periods of cognitive activity: I, "expectation;" **II,** "memorizing;" **III,** "retention." y-axes represent: In A, the same as in Fig. 1; in *B,* the relative spectral power with the maximum value of 12%; in *C,* the average spectral power during each of the periods (I, **II, III**) of activity in percent from the spectral estimates for period I.

but in 40-60% of trials, induced the decrease in the relative spectral power of the wide a band and increase in the 9-band.

In going from one stage of cognitive activity to another, the absolute values of total spectral power remained unchanged (Fig. *3B),* indicating that the relative spectral changes reflect the dynamics of their absolute values.

Similar results obtained in the replicates of the experiments in a week or two confirmed the validity of our findings.

What are the topological characteristics of the EEG spectral changes in the memory processes? First, it should be noted that the EEG changes did not show any interhemispheric asymmetry (Figs. *2A* and *2B).* At the same time, these effects varied between the occipital and parietal regions, where they were the most pronounced, and the frontal regions of cerebral hemispheres (Figs. *2A* and *2B).* The PPDS estimates decreased, predominantly, for the a-band from 80% to 40% in the subjects with high α-idex. The same tendency was typical of the initially low PPDS estimates.

The regional differences in the enhancement of 0-activity were less pronounced (Figs. *2A* and *2B;* Figs. *3A* and *3B).* However, in the group with low a-index, this effect was found to be most pronounced (the PPDS values up to 55-60%) in the occipital regions, although the frontal regions also demonstrated sufficiently high values of PPDS, up to 40-45%.

DISCUSSION

The principal finding of the present study is the wide-band changes in the EEG activity within the a- and 9-bands while performing cognitive tasks concerning memorizing and retention of visual images. In contrast to previous studies, these data were obtained by narrow-band spectral analysis, which eliminates the problem of possible opposite changes within the local frequency bands.

Despite the known polymorphism of the EEG spectrum in the ot-range [7,11] and the different behavior of the a-components under rhythmic stimulation [8, 9], in age-related memory attenuation [2, 18], Alzheimer's disease [19] and other conditions, the cognitive performance tested here brought about a decrease in the EEG activity Within the wide frequency range from 8.5 to 22 Hz in most cases. The sole evidence to bind this phenomenon with the narrow frequency range is its highest probability within the 10-11 Hz band (Fig. 2). However, it may be attributed t0 a better expression of α-activity in this particular narrow frequency range, which provides the higher dynamic range of this band and thereby facilitates the detection of significant spectral differences.

Moreover, a conventional estimation of the EEG spectral power changes, rather than the probability of their appearance, leads to the statistical contrasting of the effect within the range of most probable spectral changes. Figure *4A* illustrates the average spectral power along with PPDS estimates for the group of subjects with high a_index within the following ranges of i.5.3.5, 4.0-5.5, 6.0-7.0, 7.5-8.5, 9.0-10.0, 10.5-11.5, 12.0-13.5, 14.0-16.5, and 17.0-23.0 Hz. As can be seen, starting from 14 Hz, the average difference spectra failed to demonstrate significant changes even at the step as fine as 1.5-2 Hz, while the PPDS estimates for those very same data clearly indicated the tendency (35^40% of trials) of decreasing spectral power even for the 20 Hz frequency. It should be noted that the stochastic background value of PPDS did not exceed 20% at $p < 0.05$ (Fig. 1).

Thus, the phenomenon of EEG desynchronization, which has been known since the pioneering works of Berger [20] and has been intensively studied in recent years in cognitive tasks [2], in our experiment, was most pronounced within the narrow a-band, but could be traced within a much wider frequency range from 8.5 to 20-22 Hz. The increased frequency range of desynchronization was, apparently, revealed due to the application of a more powerful, probabilistic method of
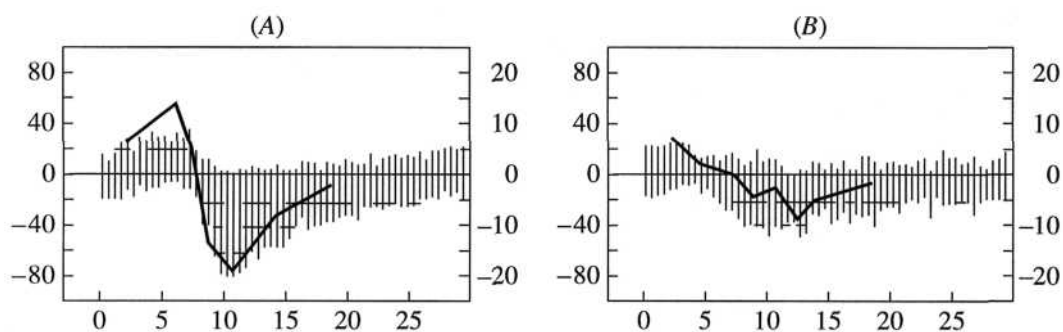
Fig. 4. Shifts in the power spectrum of the right occipital EEG during exposition of the matrix visual representation in the tests on "attention with memorizing" *(A, n= 126)* and "attention without memorizing" *(B, n = 60)* measured in PPDS units (bars, the left Y-axis) and percent of the mean relative EEG spectrum before the exposition (solid-line curve, the right Y-axis). Y-axes' scaling: 20% for PPDS and 5% for average spectrum estimates. X-axis scaling 5 Hz.

EEG analysis, since conventional analysis of the same EEG fragments showed only the well-known narrow-band desynchronization (Fig. 3, 4).

These facts look slightly surprising, especially considering the widely accepted opinion that the oc-activity recorded from a scalp can represent the combined activity of the two different generators: the thalamo-cortical and intracortical [11, 21, 22]. The data on the complex nature of the EEG a-band made it possible to suggest [6, 23] that the slow and fast components of oc-activity represent the EEG correlates of attention and working memory, respectively. However, our results did not support this suggestion: almost the whole oc-range starting from 8.5 Hz underwent uniform changes (suppression) when memorizing the matrix stimuli. The only range where different effects could be observed was that of 7-8 Hz. Its heterogeneity can be explained by its transitory nature between a- and 0-activity (Fig. 2).

Similar wide-band EEG responses involving not only the a-range activity, but also the slow component of ^-activity have also been shown in the drug research [5, 24, 25], which, in combination with the above-discussed findings, suggests the universal nature of the wide-band EEG desynchronization.

It is of interest if the effect of wide-band EEG desynchronization revealed in our experiments is typical of different cognitive tasks.

Figure *5A* shows the results of a different series of experiments, where subjects with high a-indices were presented with the same stimuli but instructed to concentrate on the brightness changes during exposure. This task required considerable attention, since, in fact, there were no changes in brightness, and the subjects had to make considerable efforts in "noticing" them. As seen, this task on attention without memorizing also induced the power decrease within the wide band from 8 to 20 Hz, but only in 40^5% of the trials. Notably, these changes occurred both during and after stimulus exposure, when the subject was to keep in memory the number of brightness changes. The standard approach

(Fig. 45) showed an expected decrease in a-activity only within the narrow a-range from 8 to 11.5 Hz.

In the third group, the passive perception of the matrices without concentrating attention and memorizing also revealed a decrease in the spectral power values over the 7-20 Hz range, but in a relatively small number of trials (up to 40%). Besides, this effect disappeared in the next 20 s after exposure (Fig. *5B).*

So, the wide-band EEG desynchronization associated with various cognitive performance reflects its nonspecific component being the activation of attention mechanisms.

It is likely that the specific components of cognitive activity, such as image memorizing and retention, were reflected in the enhanced 0-activity, observed in 45-55% of the trials (Fig. 2). Indeed, in the task on attending without memorizing, the G-range PPDS values did not exceed the level of stochastic background (Fig. 5/4). In the test on passive perception of the matrix without memorizing and attending it, the oc-desynchronization was not accompanied by changes in the 0-range (Fig. *5B).* Different behavior of a- and 0-activity has also been revealed in [26], where the 0-activity was shown to be an indicator of the episodic memory processes.

However, the 0-activity increase induced by the visuospatial or verbal tasks with memorizing correlated with the intensity of selective attention [27-29].

Within the framework of current concepts on the operational architectonics of cognitive activity, the attention and working memory, although closely inter-related, are based on different morphological and functional principles [30] and neurophysiological mechanisms [31, 32].

Since the integral activity of cortical structures is mediated both by cortico-cortical connections and limbic structures [28], it is tempting to speculate that these two basic types of central interactions can manifest themselves in the wide-band EEG desynchronization and the enhancement of 0-activity, respectively, in the complex cognitive tasks. It seems all the more likely
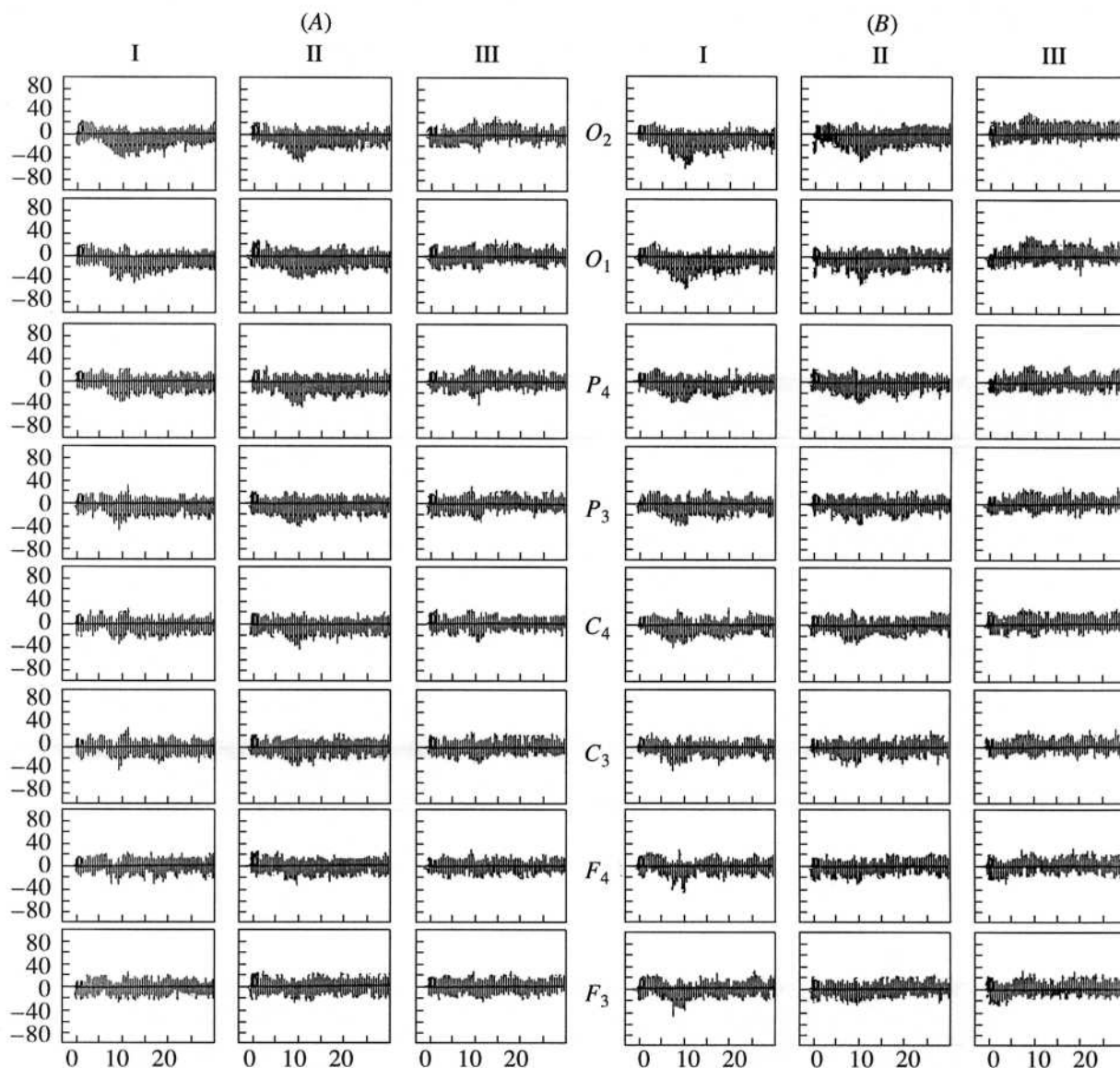
Fig. 5. Probability patterns of the narrow-band subtractive EEG spectra *(at p < 0.05)* for eight standard EEG recordings by Jasper averaged across the groups of subjects performing the task on "attention without memorizing" (4, 60 EEG recordings) and "without attention and memorizing" *(B,* 40 EEG recordings). Designations as in Fig. 1.

that some data suggest the septo-hippocampal origin of the 9-activity recorded from scalp [26, 33]. Furthermore, the hippocampal structures have been considered a cerebral substrate for visuospatial cognitive operations [30], to which our task belongs.

However, this two-component model of the EEG-correlates of memory and attention needs experimental verification as it has been reported that the decreased involvement of both processes can equally diminish the EEG desynchronization across the whole a-band [34-36].

It cannot be ruled out that the specific components of cognitive activity (memorizing—retention, selective attention and others) are consolidated with motiva-

tional and emotional components, sharing the same EEG 0-band correlates. It has been shown, for instance, that the EEG 0 activity increases with stress, the level of which has been monitored by dopamine and norepinephrine turnover [37], while medicinal treatment of neuroses has resulted in the 0-band decrease [25].

The fact that different brain functional states have EEG-correlates within the same wide-band frequency range imposes severe restrictions on their differential assessment by the EEG characteristics from one lead, However, our data showed similar PPDS behavior in all eight standard leads, excluding the extent of changes in various registration channels (Fig. 2, 3). The uniform dynamics of the task-related biopoten-

tials recorded from the scalp was observed by other authors as well [1, 3, 38].

In our opinion, it seems unlikely that the spatial homogeneity of PPDS can be attributed to the EEG recording with the linked ear reference electrode, as the occipital and frontal regions clearly demonstrated differently pronounced EEG effects (Fig. 2). It is more likely that the regional uniformity of the task-related PPDS values can be explained by insufficient sampling when averaging spectral estimates (20 s here), which allowed us to evaluate only the "tonic" components of cortical activity equally characteristic of all the cortical regions. The phasic components of the EEG-correlates of cognitive activity, which manifest themselves, for instance, in the parameters of the stationary organization of EEG fragments [39], can probably already be revealed on the level of intercortical interactions. To investigate the cooperative interregional EEG dynamics in the process of cognitive activity, it would be appropriate to use the technique of topological mapping of moments of sharp EEG changes [40]; this will constitute an objective of our future research.

CONCLUSION

(1) The narrow-band spectral analysis of human EEG showed that the memorizing of matrix images and their short-term retention in memory were accompanied by an increase in 6-activity and a decrease in oc- and (3-activity within the wide frequency range including 3.5-7, and 8.5-22 Hz, respectively.

(2) The EEG spectral changes characteristic of the memory performance showed neither interhemispheric, no intrahemispheric specificity, although they were less pronounced in the frontal regions as compared to the occipital ones.

(3) Changes in the testing conditions, which lowered the level of memory load leaving the attention intensity unaffected, resulted in the attenuation of the EEG changes in the a- and P-bands and their complete disappearance in the 8-band.

ACKNOWLEDGMENTS

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