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MULTIVARIABILITY AND METASTABILITY OF ELECTROMAGNETIC RESONANT STATES IN THE BRAIN AS A BASIS FOR COGNITION

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Abstract

The main principles of EEG/MEG piecewise stationary structure are systematized in order to form such methodological framework which accounts the main statistical properties of a spontaneous and induced EEG/MEG activity. The usage of adaptive classification of brain resonant states in the framework of outlined methodology permitted us to determine the degree to which processing of sensory stimulus and its mental image shares the same brain oscillations and the same dynamics of brain resonant states.

Thinking is the operating with mental images[1] which may be considered as mental (internal) stimuli. An activated mental image causes a neurophysiological event. Each neurophysiological event is accompanied by a particular resonant state[2] of neuronal networks, with oscillations at different frequencies. Indeed, the cortex appears to be functionally organized as a mosaic of neuronal assemblies characterized by a large variability in dominant frequencies (Pfurtscheller & Lopes da Silva, 1999; Fingelkurts et al., 2003a).

The most common way to assess the neurophysiological event in relation to external and/or internal stimulation is to investigate event-related potentials (ERP) and event-related desynchronization (ERD)/event-related synchronization (ERS) of the EEG

[1] Mental image is a quasi-perceptual experience, the result of acts of selective perceptual attention.
[2] Resonant state of the brain have been defined as an enhancement and synchronization of EEG/MEG in the conventional EEG/MEG frequencies upon sensory or cognitive stimulation (Basar, 1980)

frequency bands (Pfurtscheller & Lopes da Silva, 1999). At present, almost all methods of quantitative EEG/MEG analysis are based on certain implicit assumptions regarding the statistical characteristics of EEG/MEG, particularly with respect to the extent of stationarity and Gaussianity of the process. The efficacy of analytic techniques depends upon the degree to which such assumptions are justified by the characteristics of the EEG/MEG being analyzed (McEwen, Anderson, 1975). Unfortunately, analytic techniques such as ERP, ERD/ERS and conventional spectral analysis have a simplified statistical model for EEG/MEG activity and suffering from averaging procedures (Fingelkurts et al., 2002).

The average characteristics of a signal predominantly reflect an influence of high-amplitude segments of the EEG/MEG whereas the low-amplitude ones may be totally obscured (Kaplan & Borisov, 2003). Therefore, averaging of such estimates will most likely show the balance of diverse task-related EEG/MEG changes rather than actual "principal" processes over total signal or over all trials. Thus, regardless of how powerful or statistically significant the different averaged estimations of EEG/MEG phenomena may be, there might be difficulties in the meaningful interpretation of these if they are not matched to the EEG/MEG piecewise stationary structure (Laskaris & Ioannides, 2001). At the same time, the piecewise stationary structure of EEG/MEG may reflect the structure of functional activity of the brain (Kaplan & Shishkin, 2000; Fingelkurts & Fingelkurts, 2001).

In connection to this it is important to introduce such methodological framework which accounts the main statistical properties of a spontaneous and induced EEG/MEG activity. Although the initial idea was expressed about 30 years ago (see Bodenstein & Praetorius, 1977), it does not turned into widely used methodological approach. The main principles of this framework are the follows:

1. Piecewise stationary structure of EEG/MEG is considered as a result of "gluing" of stationary casual processes with different probability characteristics (Kaplan & Shishkin, 2000). Each stationary casual process represents a resonant state in EEG/MEG (Fingelkurts et al., 2003a). Thus, within the duration of one segment, the system that generates the EEG/MEG oscillations supposed to be in the steady stationary state (Brodsky et al., 1999). The transition from one segment to another

in this sense reflects the changes of the generator system state or changes in the activity of the two or more systems (Lehmann, 1971; Jansen & Cheng, 1988).

2. It is supposed that EEG/MEG signal consists of a restricted number of typical quasi-stationary segments (not more than 10-35 for different EEGs; see Jansen et al., 1981; Fingelkurts et al., 2002, 2003a), which usually do not exceed 1-2 sec (McEwen & Anderson, 1975; Inouye et al., 1995). In such a way, the dynamics of brain activity can be considered as a sequence of relatively stable and fixed EEG/MEG resonant states.
3. It was shown that different types of EEG/MEG resonant states had different importance to the brain – their occurrence is less or more probable for particular functional state of the brain (Fingelkurts et al., 2002). Apparent "switching" from one dynamic to another is characterized as *multivariability*, with new patterns being continually created, destroyed, and subsequently recreated (Keslo, 1995). This finding relates to the discrete (but not independent) work of the different morphological brain systems (Dierks et al., 1997; Strik et al., 1997) and also cognitive systems (for reviews see John, 2001; Fingelkurts & Fingelkurts, 2001). Perhaps, the high multivariability of EEG/MEG resonant states indicates a wide range of the possible variations in current brain state or activity.
4. It has been suggested that particular sequences of several EEG/MEG resonant states appeared in consistent groupings (steady bundle with each other) and comprise more integral blocks of EEG structural organization (Sandersen et al., 1980; Lopes da Silva, 1981; Jansen & Cheng, 1988). A temporary stabilization in the resonant states reflects the maintaining of the relative stability in the neurodynamics within that particular time interval on both a micro- and macro-level.
5. It was shown the co-existence of a high multivariability of the EEG parameters with a simultaneous stabilization of these parameters in time. A high incidence of the neighboring resonant state types is restricted by the limited resonant state set and by a 50% reduction in the functionally active resonant states (Fingelkurts et al., 2003a). Thus, the brain dynamics may be viewed here as balancing between multivariability and metastability (Bressler & Kelso, 2001).

6. It is suggested that quasi-stationary segments reflect the operational elements (Basar & Bullock, 1992) or basic blocks (Lehmann et al., 1987) of nervous activity. In total, available data testify to indubitable functional significance of the segmental EEG architectonics (see reviews Kaplan & Shishkin, 2000; Fingelkurts & Fingelkurts, 2001).
7. Thus the operational acts of behavioral and mental activity may originate in the periods of short-term *metastable states* of the whole brain and its individual subsystems (see review Kaplan, 1998; Fingelkurts & Fingelkurts, 2001).
8. It has been shown that the parameters of the relative presents of the individual EEG/MEG segments of each type, and regularities of its alteration in the analyzed EEG/MEG are provide more adequate and accurate insights into the characteristics of the brain operational activity in norm and pathology (Jansen, 1991; Fingelkurts et al., 2002, 2003a) and possible drug effects on brain dynamics (Kaplan et al., 1996).

Taking into account this methodological framework which permits describe adequately a piecewise stationarity of EEG/MEG, it is justified to obtain an entire set of individual short-term spectra of various types in accordance with the number of stationary EEG/MEG segments. In this case, one segment may be considered as single event in EEG/MEG phenomenology from viewpoint of its spectral characteristics. A subsequent adaptive classification of spectral patterns (SP) in the whole EEG/MEG would result in probability classification profile (PCP) – the histogram of the relative presence of each SP type (Fingelkurts et al., 2003a).

Adaptive classification technique includes several adequate correction algorithms for considerable reduction of the 100% variance of the single spectral estimations (see Fingelkurts et al., 2003a). This justifies the usage of individual short-term SPs and increases the sensitivity of this analytical approach for EEG/MEG dynamics. Adaptive classification technique (SCAN-M software, Moscow State University; Kaplan et al., 1999a) results in *m* classes of SPs. Considering that a single EEG spectrum illustrates the particular integral dynamics of tens and hundreds of thousands of neurons in a given cortical area at a particular point in time (Dumermuth & Molinari, 1987), the SPs within each class can be considered effectively generated by the same dynamics, with the same driving force. Whereas SPs from different classes can be considered to have had different driving forces and therefore have been effectively generated by different dynamics. Each SP can be labeled by the index of the class to which it belongs. Thus, a sequence of SP labels that represents the sequence of EEG/MEG resonant states through which the system passes can be obtained.

Described methodological approach is especially suitable for analysis of non-stationary signals and is a unique tool for the investigation of dynamic changes of brain activity. Dynamic aspect of brain activity during mental imagery[3] was not yet addressed. This fact emphasizes us to use this approach to study brain mechanisms of mental imagery. One issue currently under debate is the degree to which imagery and sensory processing share the same neural circuitry and oscillations. An increasingly large body of data exists which demonstrates that real and imagined visual objects share the same neural substrates (Ishai & Sagi, 1995; Raij, 1999; Ito, 2000; Wheeler et al., 2000) and that visual imagery can resemble the perception of real visual stimuli (Farah et al., 1988). At the same time, the role of brain oscillations in imagery and sensory processing are not clear.

In the present work we studied the degree to which processing of sensory stimulus and its mental image shares the same brain oscillations in multistage cognitive task. This task comprised three consecutive stages (20 sec. duration each): 1) the waiting of the presentation of matrix visual stimulus; 2) the presentation and memorizing of matrix visual stimulus; 3) keeping in mind the image of memorized stimulus. The subject was then asked to reproduce the pattern by touching squares in the matrix with a special pencil. The visual stimuli presented in front of the subjects to memorize were non-verbalizable matrices composed of nine square elements presented on a matrix screen. A total of twelve matrix compositions were presented to each subject. The combination of the squares was selected quasi-randomly. Twelve one-min electroencephalograms (EEGs) for twelve subjects were registered in eight standard locations ($F_{3/4}$, $C_{3/4}$, $P_{3/4}$, $O_{1/2}$) during the three stages of the cognitive task. All EEG electrodes were referred to

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[3] Mental imagery is experience that resembles perceptual experience, but which occurs in the absence of the appropriate stimuli for the relevant perception (Finke, 1989).

linked ears. Raw EEG signals were amplified and filtered in 0.5-30 frequency range and digitized at a sampling rate of 128 Hz by a 12-bit analog-to-digital converter. The impedance of the recording electrodes was always below 5 kΩ. The presence of an adequate EEG signal was determined by visual inspection of the raw signal on the computer screen. Individual power spectra were calculated in the range of 0.5–30 Hz with 0.5-Hz resolution (61 values), using FFT with 2-sec Hanning window shifted by 50 samples (0.39-sec) for each selected EEG channel. As a result, individual power spectra with a 0.5-Hz step were calculated for three consecutive 20-sec fragments of the 1-min EEG during multistage cognitive task. Individual spectral patterns (SP) were obtained for each subject and each EEG channel separately. These SPs formed the multitude of the objects for further classification procedure. The parameters of variability within SPs during different functional states and experimental tasks were estimated at two stages. At the first stage, the adaptive classification of sequential single EEG spectra was performed in each EEG channel separately by reference to a set of standard SPs. Details of this procedure can be found in Fingelkurts et al., (2003a). At the second stage, the probability classification profiles (PCP) of SPs for each EEG location in each subject and for the group of subjects as a whole were calculated. An index was calculated as the number of cases of SP type as a percentage of the total amount of all SPs in any given EEG channel. PCPs were averaged for each subject separately for each EEG channel and condition (stage of the cognitive task). After this, the data for each condition was averaged across those subjects which showed similar results.

The usage of methodological approach and adaptive classification analysis described above permitted us to study the dynamics of the following indices:

1. The percentage of *polyrhythmic/disorganized activity* – presented by polyrhythmic EEG spectral patterns (Fingelkurts et al., 2003a). A polyrhythmic spectral pattern constitutes a pattern, where peaks occupy majority of the frequencies within the studied range. Such spectral pattern indicates a mixture of activity of small neuronal subpopulations each with its own mode (Tirsch et al., 2000).
2. *The total number of SP types*. This index indicates how many different brain oscillation types participate in given EEG.

3. The number of *the most probable SPs* – indicates the most “preferred oscillations” of the brain during particular state/task or as a response to a particular stimulus (Fingelkurts et al., 2002; Fingelkurts et al., 2003b in submission).
4. *Types of functionally active SPs* – spectral patterns that provide the changes of the steady SP combinations during the changes in the brain’s functional state (Fingelkurts et al., 2003a).
5. *The relative incidence of change in type of SPs* - presents an estimation of the rate of relative alteration in the type of SPs for a given EEG (Fingelkurts et al., 2003a).
6. *Period of the temporal stabilization* for various SP types in local EEGs - shows the time during which the brain “maintains” the stabilization period of neuron’ activity in a given cortical site (Fingelkurts et al., 2003a).
7. *Period of spatio-temporal stabilization for SPs in multichannel EEG* – caused by formation of the cortical spatial modules, within which steady relations are formed by the character of mutual stabilization between the types of EEG spectral description in each EEG channel independently of their correlation and coherence (Kaplan et al., 1999b).

The indices 1-5 characterize multivariability, whereas the indices 6-7 mark metastability of electromagnetic resonant states in the brain (Fingelkurts et al., 2003a).

The goal of this study was to determine the degree to which processing of sensory stimulus and its mental image shares the same brain oscillations. To explore this issue, we compare second and third stages of present cognitive task. At the first case, a subject should act with perceptual stimulus, whereas at the second case, a subject needs to act with the mental image of the actual stimulus. The result of the analysis of the indices described above for different stages of the cognitive task is presented in the Figure 1.

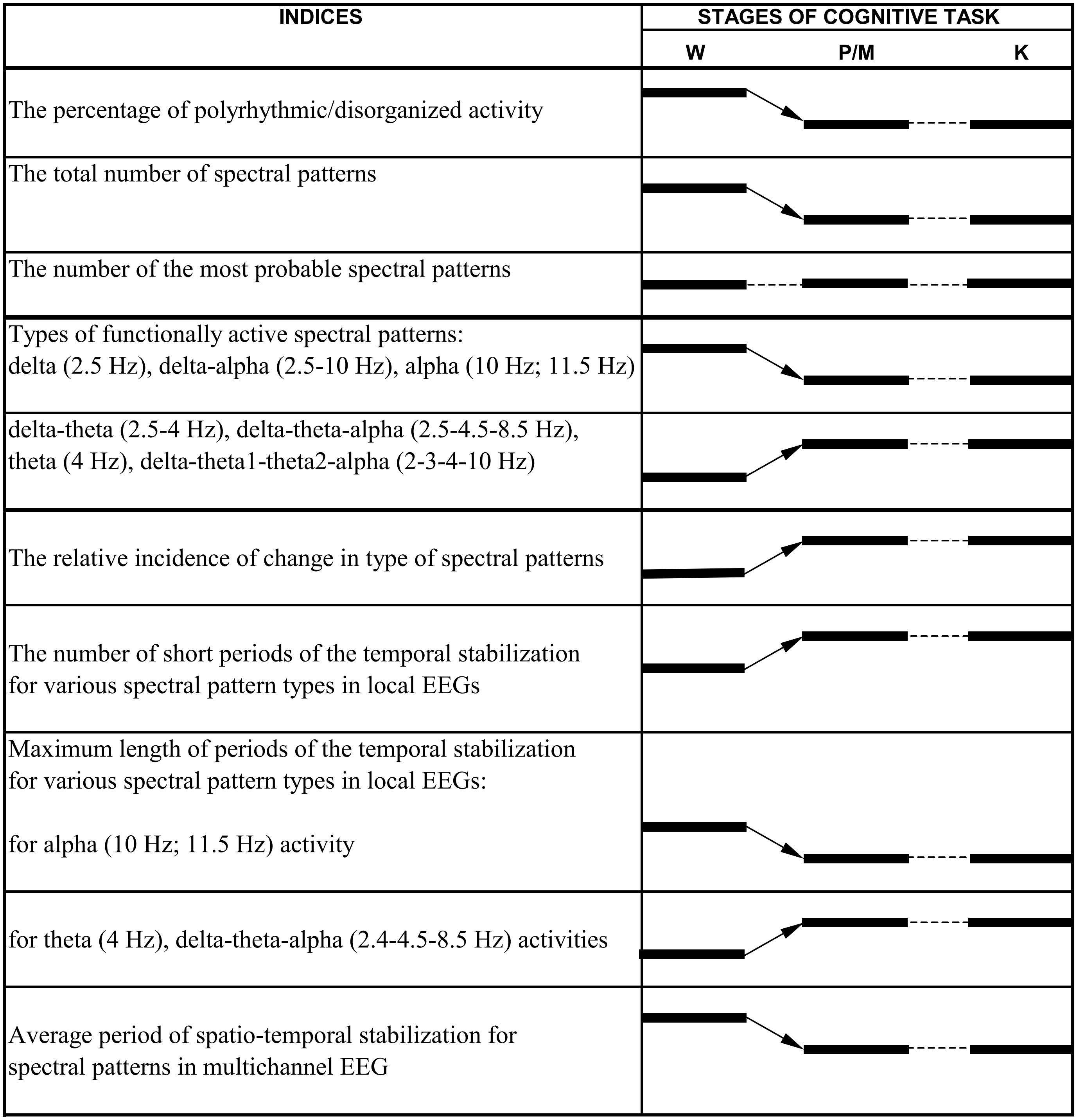

Figure 1. The scheme of the changes of the studied indices during three stages of cognitive task. W – waiting of the presentation of the matrix visual stimulus; P/M – presentation/memorizing of the matrix visual stimulus; K – keeping-in-mind the mental image of the actual stimulus. Solid arrow indicates significant (p<0.01-0.001) changes, and doted horizontal line marks the absence of the changes or non-significant changes.

The main finding was the following: processing of the perceptual stimulus and its mental image has no differences in accordance with all studied indices. At the same time, inspection of the individual EEG recordings demonstrated that processing of the perceptual stimulus and its mental image has different temporal dynamics of SPs (Fig. 2).

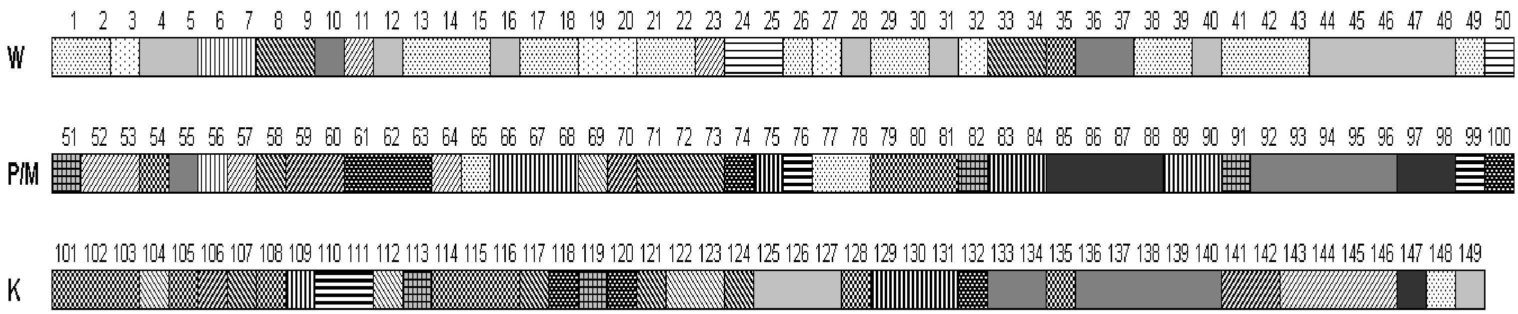

Figure 2. The sequence of spectral pattern types in O1 EEG channel for the three stages (20-sec duration each) of the cognitive task. Different spectral pattern types are marked in different colors (the same spectral pattern types have the same color). Numbers indicate 149 spectral patterns calculated on 2-sec EEG epochs with 50 points shift (0.39-sec) for one-minute EEG.
W – waiting of the presentation of the matrix visual stimulus; P/M – presentation/memorizing of the matrix visual stimulus; K – keeping-in-mind the mental image of the actual stimulus.

These findings can be understood in terms of a common rhythmic system with multiple resonant states which is "used" by the brain for processing both perceptual stimulus and its mental image. Our findings provide experimental evidence to support the hypothesis that mental image may be considered as an internal stimulus which is processed similar to a perceptual (external) stimulus (Hesslow, 1994). At the same time, temporal dynamic of rhythmic systems is different for processing of perceptual stimulus and its mental image. This result indicates clearly that temporal contribution of brain micro-operations necessary for information processing is unique for each case, depending on the situational context.

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