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Title: **Operational Architectonics of the Human Brain Biopotential Field: Towards Solving the Mind-Brain Problem**

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ABSTRACT

Operational Architectonics of the Human Brain Biopotential Field: Towards Solving the Mind-Brain Problem

The understanding of the interrelationship between brain and mind remains far from clear. It is well established that the brain's capacity to integrate information from numerous sources forms the basis for cognitive abilities. However, the core unresolved question is *how* information about the "objective" physical entities of the external world can be integrated, and *how* unified and coherent mental states (or Gestalts) can be established in the internal entities of distributed neuronal systems. The present paper offers a unified methodological and conceptual basis for a possible mechanism of how the transient synchronization of brain operations may construct the unified and relatively stable neural states, which underlie mental states.

It was shown that the sequence of metastable spatial EEG mosaics does exist and probably reflects the rapid stabilization periods of the interrelation of large neuron systems. At the EEG level this is reflected in the stabilization of quasi-stationary segments on corresponding channels. Within the introduced framework, physical brain processes and psychological processes are considered as two basic aspects of a single whole informational brain state.

The relations between operational process of the brain, mental states and consciousness are discussed.

Key Words: adaptive segmentation, binding problem, coherence, EEG microstructure, functional integration, metastability, neocortical dynamics, nonstationarity, operational synchronization, spatial scale.

Abbreviations:

EEG – electroencephalogram (electroencephalography),
ERD/ERS – event-related desynchronization/event-related synchronization,
ERP – event-related potential(s),
FM – functional module,
FOK – feeling-of-knowing,
HH – Hodgkin-Huxley equation,
ICA – independent component analysis,
IOS – index of operational synchrony,
IOSBR – index of operational synchrony of the basic EEG rhythms,
LFP – local field potential(s),
LTP – long-term potentiation,
MEG – magnitoencephalogram (magnitoencephalography),
NCC – neural correlates of consciousness.
NMDA – N-methyl-D-aspartate,
OM – operational module(s),
OS – operational synchrony,
RTP – rapid transitional process(es),
TOT – tip-of-the-tongue,

1. Introduction

It has been nearly two centuries since the publication of the book “Reflex of Human Brain” by M. Sechenov, which opened the scientific cognition era of “elements of thought” in the terms of concrete nervous activity acts (Sechenov, reprint of 1956). Yet through the beginning of the twenty-first century, the question about the delicate edge between “corporal” nervous impulse and “ethereal” mental or cognitive act has remained open. That is why a stable and growing interest in brain research and, in particular, in new approaches and methods of investigation into brain activity has been observed in recent times. It is believed that new approaches will permit a description of the internal representation of the external world and of mental states using objective investigation tools.

Recent neuroscience studies have shown that the internal construction of external space requires integration of information from multiple sensory modalities (Sams et al., 1991; Driver and Spence, 1998) and synchronous activity of many brain areas (Freeman, 1991; Schillen and König, 1994; Engel et al., 1999; Singer, 1999). It has even been suggested that this so-called “binding concept” may solve the unity of conscious perception (see critical review by Revonsuo, 1999 and 2000b). However, the core unresolved question is *how* information about the “objective” physical entities of the external world can be integrated, and *how* unified and coherent mental states (or Gestalts) can be established in the internal entities of distributed neuronal systems (Engel et al., 1999).

The present paper offers a unified methodological and conceptual basis for a possible mechanism of how the transient synchronization of brain operations may construct the unified and relatively stable neural states, which underlie mental states.

2. EEG and cognitive acts

Considering the enormous complexity of the brain, we have followed the idea of Nunez (2000) that macroscopic variables of brain activity require appropriate (macroscopic) scale of analysis. Here the electroencephalography (EEG) (or magnetoencephalography (MEG)) is still the most robust tool for studying cognitive events (Gevins and Cutillo, 1986, 1995). At first, EEG/MEG provides a very large-scale measuring of neocortical dynamic functions (Nunez, 2000). Secondly, the synchronization or binding of distinct neural networks is reflected in the EEG (Nunez, 1995; Jirsa and Haken, 1997). Thus, EEG-methodology provides possible connections between the cell assembly theory (Hebb, 1949; Singer, 1993, 1999) and the ‘field’ concept from Gestalt psychology (Scott, 1995). Thirdly, intracranial data provide no more information than is obtained from the scalp (for details see Nunez, 1995). Moreover, intracranial data is often uncorrelated or only weakly correlated with cognition and behavior (Nunez, 1981; Freeman, 1991). Therefore, the macroscopic physics of neocortex (Nunez, 1995), chaos theories of the brain (Freeman, 1991; Tsuda, 2001) and ‘metastable’ dynamic theory (Kelso, 1995; Bressler and Kelso, 2001) may suggest the answer on the difficult question: at which level of organization (the single neuron, the patterns of activity in neural populations or temporal synchronicity of neural activity) does the nervous system organize itself into functionally and behaviorally relevant units (Revonsuo, 1999). It becomes obvious that the level of organization at which cognition, mind and “consciousness resides might be a highly organized macro-level electrophysiological phenomenon in the brain, realized by the coordinated electrical activity of specific populations” (Revonsuo, 2001, p. 5).

Due to the speed of elementary cognitive acts, only EEG and MEG, – among the most modern methods for human brain activity research, – which have the lowest inertia, may be adequate methods for the analysis of mobile dynamics of information-processing brain activity (Lopes da Silva, 1987; Nunez, 2000). For critical discussion about disadvantages of indirect imaging methods see Revonsuo (2001). Since the changes of neuronal cell membrane potentials underlie signal exchange between the neurons, they are absolutely synchronous with the dynamics of the brain's information processing (Nunez, 1995, 2000). The fluctuations of the total potential of neurons registered at the surface of the head, therefore, follow the activity of neuronal networks without time delay.

In the first investigations of human EEG (Adrian and Mattews, 1934; Adrian and Yamagiwa, 1935) highly mobile dynamics of alpha-spindles (Lehmann, 1980; Gath et al., 1983; Jung et al., 1997) suggested to scientists "the symphony metaphor" (Nunez, 1995) of electrical brain activity where "switching on/turning off" of EEG rhythmic components is the "echo" of operational work of discrete morpho-functional systems (Kaplan et al., 1997b; Kaplan et al., 1998; Fingelkurts, 1998). Thus, the operational logic of unrolling brain functional states during the realization of behavioral or psychological acts, assumes that on the EEG-level the successive operations of nervous activity may be traced in the palette of segment-description dynamics of corresponding EEG rhythmic components (Kaplan and Shishkin, 2000; Finglekurts and Fingelkurts, 2001).

3. EEG nonstationarity and rapid transitional processes

Special examination and analysis of EEG nonstationarity (see review by Kaplan, 1998) has lead scientists to the new idea that the EEG is a highly structured process where each quasi-stationary segment may reflect quite definite discrete stages of functional brain activity – operation (Barlow, 1985; Kaplan and Shishkin, 2000, Fingelkurts and Fingelkurts, 2001). This means that a recorded signal may be presented as a result of "gluing" of stationary casual processes with different probability characteristics (see review by Kaplan, 1999).

In order to reveal the segment boundaries in the EEG, segmentation methods have been used (see reviews by Barlow, 1985; Fingelkurts, 1998; Kaplan and Shishkin, 2000). There are several segmentational approaches: a) EEG segmentation using fixed intervals (Jansen et al., 1981), b) adaptive segmentation, which consists of parametric (Bodenstein and Praetorious, 1977; Jansen, 1991; Inouye et al., 1995) and nonparametric methods (Creutzfeldt et al., 1985). However, the majority of these approaches have serious disadvantages (see Appendix 1).

To overcome these disadvantages the original technology of the adaptive nonparametric EEG segmentation was developed (Kaplan et al., 1997b; Shishkin et al., 1997; Fingelkurts, 1998; see Appendix 2) on the basis of the theory of the analysis of sharp changes or ***rapid transitional processes*** **(RTP)** in the piecewise stationary structure of the signals (Brodsky and Darkhovsky, 1993, 2000). Transition intervals are supposed to be of minor length, and therefore can be treated as a point (or near-point). RTP in such a way are, in fact, the markers of the boundaries between quasi-stationary segments and correspond to especially informative “events” of the brain systems dynamics, namely to their “switches” from one *operation* of the neuronal networks to another (Basar, 1992; Lehmann, et al, 1995; Wright and Liley, 1996; Nunez, 2000; Kaplan and Shishkin, 2000). Thus, operation sequences in certain cortical areas could be reflected in quasi-stationary segments of local EEGs.

It is necessary to note that considering the composite polyphonic character of the EEG signal, each frequency EEG component has its own segmental structure (Kaplan et al., 1998; Fingelkurts, 1998), which seems to be indicative of the discrete operations of different morpho-functional brain systems. Thus, covert dynamics of the operational activity of the cortex, which cannot be disclosed by usual methods of EEG analysis, can now be studied.

4. Operational synchrony and metastable states

Experimental evidence suggests that complex cognitive functions, functional and behavioral acts are organized at a global level (large-scale cortical networks) in the brain and that they arise from operations organized in localized brain areas (Luria, 1980; Damasio and Damasio, 1994; Wright and Liley, 1996; Tallon-Baudry et al., 1997; Bertrand and Tallon-Baudry, 2000; Bressler and Kelso, 2001). In that sense, the estimation of the spatio-temporal organization of the cortical EEG is one of the most promising approaches for studying the integrative activity of the human brain. The methods of the analysis of simultaneous joint coordination of several or many EEG channels directed toward the study of the integral organization of the cortical bioelectric field are of special interest. The polycorrelational character of the morpho-functional organization of neuronal networks (Nunez, 2000; Kaplan and Shishkin, 2000) reveals the spatio-temporal aspect of correlation between EEG segmental processes.

It seems highly possible that the segment sequences in different EEG channels should, to a certain extent, be synchronized (or near-synchronized), forming the short-term *metastable* topological combinations, – so-called ***operational modules*** **(OM)** of different size (number of cortical areas involved) and lifetime (Kaplan and Shishkin, 2000; Fingelkurts and Fingelkurts, 2001; Fingelkurts et al., in preparation). The simultaneity of the occurrence of the RTP generated by different cortical systems gives the evidence of their participation in the same functional act (Kaplan et al., 1997b). A qualitative description (see Appendix 3) of this type of synchrony, which was called ***operational synchrony*** **(OS)**, provides the means for a radically new insight into co-operation of the brain structures (for the first time this notion was introduced in Kaplan et al., 1997b, see also recent review by Kaplan and Shishkin, 2000) and permits the registration of trajectories of the proper “atoms of thought” (Lehmann, 1991). Here the emphasis is made upon the *direct estimation* of the coupling of inherent elementary operations going on in different cortical areas, instead of routine phase-frequency synchrony in the terms of correlation and coherency (Kaplan et al., 1995; Fingelkurts, 1998; Kaplan and Shishkin, 2000).

Thus, the evidence of available data (we return to this below) suggests that the 'continuous' behavioral and mental activity consists of discrete mental/behavioral acts which originate in the periods of *short-term metastable states* of the whole brain and its individual subsystems (Kaplan and Shishkin, 2000; Fingelkurts and Fingelkurts, 2001), when the numbers of degrees of freedom of the neuronal networks are maximally decreased (Kaplan, 1998; Fingelkurts, 1998).

5. Theoretical considerations and other approaches

Meanwhile, it was understood prior to present work that metastable dynamics is distinguished by a balanced interplay of integrating and segregating influences (Kelso, 1984, 2000; Haken et al., 1985). Metastability occurs due to the competitive 'struggle' between the tendency of each component part to maintain its individual spatial and temporal properties (Bressler and Kelso, 2001).

Many scientists try to investigate the brain's metastability. Thus, Bressler and Kelso (2001) used event-related local field potentials (LFP) as the signal of interest and estimated their spectral coherence and phase. Tononi et al. (1998) used the theory of complexity and coherency approach to investigate functional integration. But in a strict sense the coherence value indicates only the linear statistical link between signals in a frequency band and therefore can characterize (in the framework of the 'symphonic' metaphor of EEG, Nunez, 1995) only the similarity between sets of 'orchestral instruments' being used by neuron ensembles of cortical areas, not the participation of these ensembles in the performance of a single ‘musical work’ or a common functional/behavioral act (for critical discussion see Kaplan et al., 1997b).

Another problem concerns the averaging of EEG parameters, which might not only mask the dynamics of possible EEG correlates of cognitive processes, but also give rise to ambiguous interpretations when examining the event related potentials (ERP) or event related desynchronization/synchronization (ERD/ERS) (for critical discussion see Fingelkurts et al., in submitting). All these factors lead to significant difficulties in the interpretation of data. Therefore, applying averaging approaches to investigate the integrity of brain states makes results ontologically unpromising.

There are several theoretical studies in which scientists have built models of how brain functional specialization and integration leads to a unified, integrated mental state. For instance, Grossberg (2000) proposed the hierarchical intrastream interactions and parallel interstream interactions for brain self-control and stable self-organization. Friston (1997), using computer modeling, proposed that the complex nature of nonlinear systems like the brain include metastability. Here it is necessary to note, that many brain theories have avoided the matching of theoretical with experimental scales, and should be categorized as metaphorical rather than genuine brain theories (Nunez, 2000). Neuroscientists also have not paid enough attention to scale: for example, activity of isolated neurons or small networks has been extrapolated to large neuronal systems without justification.

Current applications of EEG computer analysis suggest a number of ‘geometric’ estimations of joint coordination of local EEG recordings calculated with the use of factor analysis (Manmaru and Matsuura, 1989; Lazarev, 1997), independent component analysis (ICA) (Sato et al., 2001; Callan et al., 2001) and multivariate liner regression (Wada et al., 1996; Lehmann et al., 1995) of the primary EEG characteristics as well as on the basis of three-dimensional dipole decomposition of multichannel EEG (Lutzenberger, 1997) and ideas about chaotic dynamics of an EEG vector composed of simultaneous momentary counts of local EEG recordings (Matousek et al., 1995).

However, all these approaches inevitably come up against the problem of the nonstationary nature of the EEG (Kaplan et al., 1999): regardless of how powerful or statistically significant different estimations of coordination between local EEG patterns may be, there are enormous difficulties in their meaningful interpretation if the EEG piecewise stationary structure is not considered.

From our point of view the Lehmann's spatially oriented segmentation of cortical potentials is a more appropriate approach for estimating global mutual coordination of local EEGs (Lehmann, 1971; Lehmann, 1987; Lehmann et al., 1993). This technique is based on the calculation of the spatial localization of the vector of the maximal potential difference (Lehmann and Koenig, 1997). Periods of stabilization of this vector are assumed as stable brain microstates. But it should be mentioned, that in the context of this method, local EEG sites do not participate equally in the formation of the resulting dipole vector and this has not been justified from the viewpoint of indubitable neurobiological equivalence of cortical areas (Kaplan et al., 1999).

Available data suggest the following theoretical and experimental considerations: 1) the signals from the large number of functionally specialized neurons' groups distributed over many brain areas are rapidly integrated to generate a coherent, multimodal scene (binding problem) (Gray et al., 1989; Crick, 1984; Damasio, 1990; Smolensky, 1990; van Gelder, 1990; Engel et al., 1999; Singer, 1999; Buckner et al., 2000), 2) functional segregation (local processes) and integration (global processes) occur at multiple spatial and temporal scales, and both characterize most brain phenomena (Zeki, 1990, 2001; Nunez, 1995; Silberstein, 1995; Friston et al., 1995; Wright and Liley, 1996; Tononi et al., 1998; Haken, 1999; Nunez, 2000), 3) the functional clusters and neuronal complexity do exist

(Lutzenberger et al., 1995; Gell-Mann and Lloyd, 1996; Tononi et al., 1994, 1998), 4) metastability is characterized by short transient periods of stability (Kelso, 1984, 1995, 2000; Haken et al., 1985; Friston, 1997; Bressler and Kelso, 2001).

However, until recently there has been no appropriate neurophysiological methodology, which matches all of these theories and experimental data. Although these theories may be suitable for explaining some aspects of mental phenomena, they cannot be applied to phenomenal content, which is "hidden" in the complex microscopic structure of biopotential brain field. On the EEG level this structure is reflected in nonstationarity, where unrolling mental states may be traced in the consequences of segment-description dynamics of corresponding EEG rhythmic components (Kaplan et al., 1997b; Fingelkurts, 1998; Kaplan and Shishkin, 2000).

The methodology introduced in the present paper allows revealing such a level of organization in the brain (several paragraphs below we will try to show that this level of brain organization is isomorphic with the phenomenal level of experience). Moreover, this framework introduces new levels of description and of explanation that capture phenomenal level of organization in the brain. The methodology and conceptual framework described above (see "*EEG nonstationarity and rapid transitional processes*" and "*Operational synchrony and metastable states*", and Appendixes 2, 3), permit – perhaps for the first time – to emphasize the estimation of elemental operations going on in different brain areas and their *inherent binding* into metastable operational modules which underlie mental states. This approach was first proposed in 1995 (Kaplan et al., 1995) and later developed in a number of publications (Kaplan et al., 1997b; Shishkin et al., 1997, 1998; Fingelkurts, 1998; Kaplan, 1998; Kaplan et al., 1999; Fingelkurts et al., 1998, 2000; Kaplan and Shishkin, 2000; Fingelkurts and Fingelkurts, 2001; Kaplan et al., 2001; Fingelkurts et al., in preparation). Experimental application of this methodology has confirmed a large number of the expectancies.

6. Brief review of the experimental results

Application of the novel technique of nonparametric EEG segmentation demonstrated its high sensitivity for estimating (in an unsupervised regime) the dynamics of structural changes in spontaneous EEG and EEG associated with cognitive processes (Kaplan and Shishkin, 2000). It was shown that spontaneous EEG consists of quasi-stationary segments (reflecting ‘internal’ events), the majority of which had a duration less than 1 sec (Kaplan et al., 1997b; Shishkin et al., 1997, 1998; Fingelkurts et al., 1998). Additionally, the specific proportions of the stationary segments of the different durations strongly vary between different cortical areas (Fingelkurts et al., 1998; Fingelkurts, 1998). The example given in Fig. 1 illustrates the detection of rapid transition processes (RTP) in EEG.

The changes in the number and duration of EEG segments were also demonstrated for different sleep stages (Kaplan et al, 2001). It was observed that during the 4th stage of sleep the average interval between neighboring RTP was 68-85% shorter than these same intervals during the 2nd sleep stage (Kaplan et al, 1997a). Moreover, it was shown that the nonparametric segmentation in combination with cluster analysis enables to obtain a clear picture of the hierarchical macrostructural organization of sleep, which is impossible to deduce from the unsegmented EEG data (Kaplan et al., 2001)

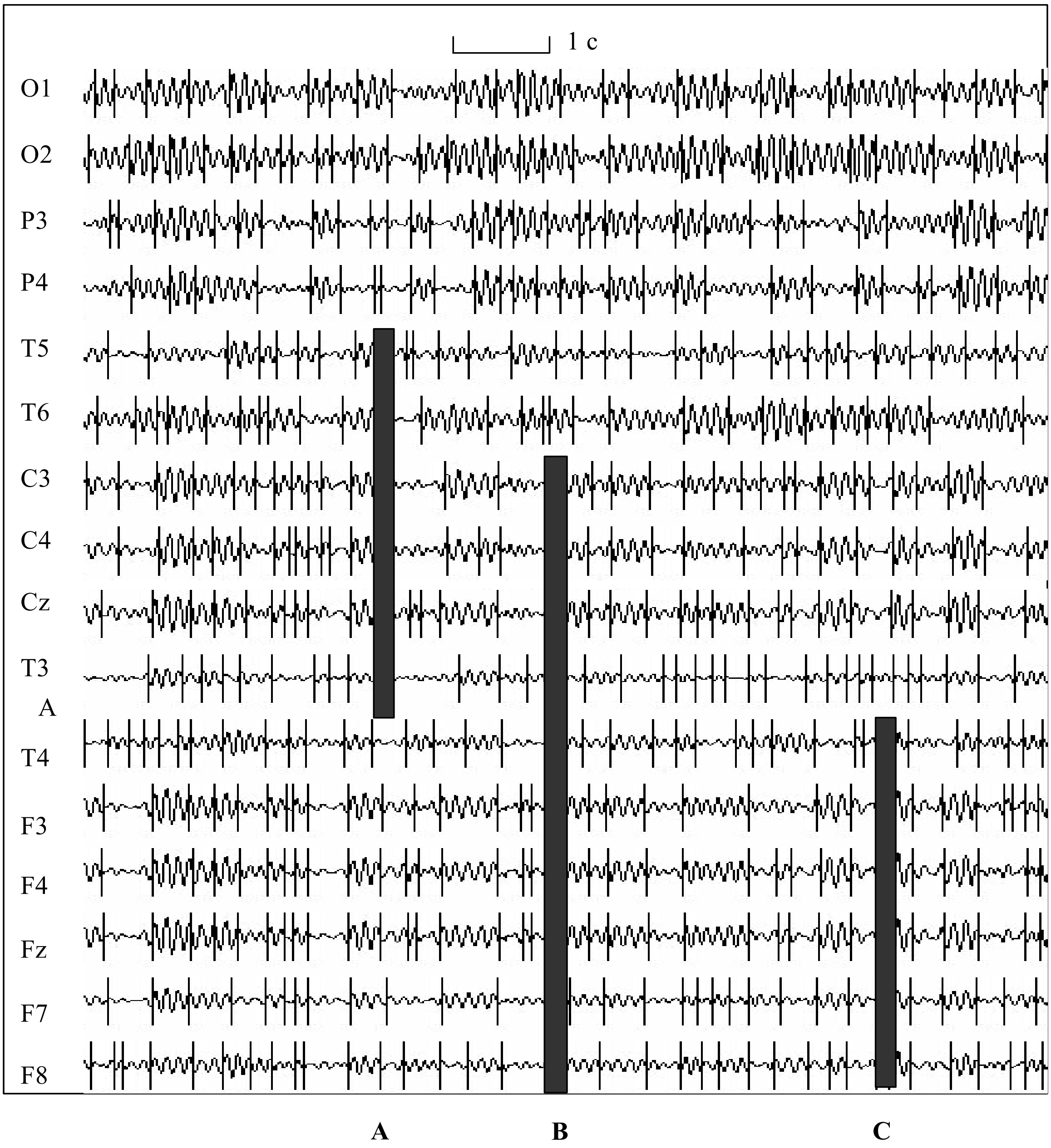

Fig. 1. Typical fragment of 16-channel EEG record (filtered in alpha band diapason: 7-13 Hz) with automatically detected rapid transition processes (RTP). “A”, “B” and “C” illustrate some cases of RTP coincidence between different EEG channels.

In the cognitive tasks RTP was used to detect ‘internal’ events (the brain activity transformations) following ‘external’ events, such as presentation of a stimulus to a subject or his/her movements (pressing a response button). Specific variation in the number of RTP across different stages of cognitive activity was observed (Shishkin et al., 1997, 1998;

Fingelkurts et al., 1998; Kaplan and Shishkin, 2000; Fingelkurts et al., in preparation). These data suggest a functional significance of segmental EEG architectonics during both spontaneous (stimulus independent) and induced (stimulus dependent) brain activity.

However, considering the composite polyphonic character of the EEG signal, one needs to remember that frequency heterogeneity influences the segmental structure of the EEG signal (Fingelkurts, 1998; Kaplan and Shishkin, 2000). Precisely discrete frequency components play the main role in 'switching on' and 'turning off' of discrete morpho-functional operations of brain systems (Kaplan et al., 1998; Fingelkurts, 1998). It was shown that segment flows for each of the EEG frequency component are more or less correlated, depending on the character of the information-processing brain activity (Fingelkurts, 1998).

Using the information about the structural peculiarities of the EEG signal, it is possible to study inter-cortical co-operations that are revealed in the synchronization or coupling in time of RTP in multi-channel EEG-recordings. In modeling investigations (the human EEG recorded from longitudinal and transversal electrode arrays) it has been shown that the index of operational synchrony (IOS) reflects the morpho-functional peculiarities of the different cortical areas of the brain rather then the processes of the volumetric realization of the electrical field in brain tissue (Fingelkurts, 1998; Kaplan et al., 2000). The relationship between the IOS and interelectrode distance was not monotonous. The IOS depended also on the extent of morpho-functional similarity between cortical areas.

In cognitive tasks it was shown that a change in the cognitive activity produces considerable reorganization of the operationally synchronized (OS) pairs (Kaplan et al., 1997b; Fingelkurts, 1998; Kaplan and Shishkin, 2000; Fingelkurts et al., in preparation). This reorganization is seen as a spatial widening of the coupling between cortical areas when visual images are memorized and a considerable narrowing and specialization of the links when a visual image is being retained in the memory (Fig. 2).

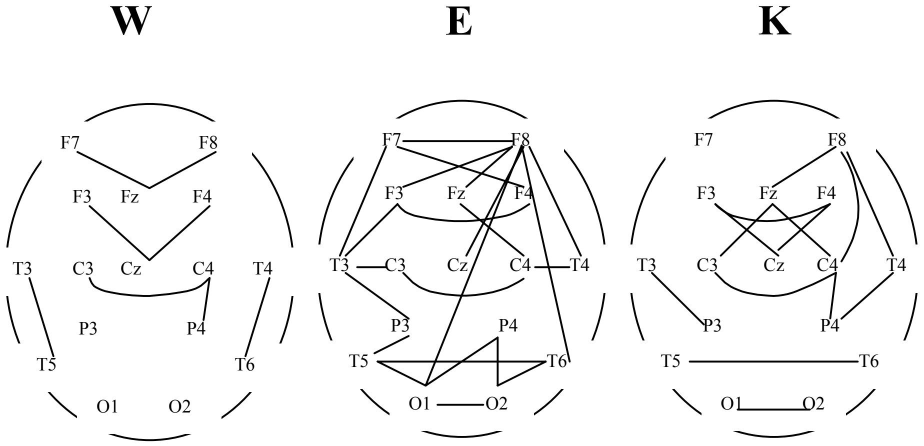

Fig. 2. Maps of the operational synchrony configurations for pair EEG combinations during memory task periods, which were presented in chronological sequence: W - waiting period, E – encoding period, K – keeping-in-mind period. The lines indicate cases of upper-threshold IOS (IOS > 2, $p < 0.001$).

It has also been shown that spatial configurations of more then two cortical sites with common EEG channels, – so-called operational modules (OM), vary significantly within relatively short time intervals. Such dynamics depend on the functional state of the subject and the experimental task (Fingelkurts, 1998, Fingelkurts et al., 1998, 2000; Kaplan and Shishkin, 2000; Fingelkurts et al., in preparation). The relevant to different memory stages (encoding, retrieval, keeping-in-mind, identification) OMs were obtained. For example, a considerable reorganization of the OS process was observed (Fig. 3) during the transition from one memory stage to another (Fingelkurts et al., 1998, 2000; Fingelkurts et al., in preparation). Moreover, the IOS appeared to be sensitive to the individual level of the subjects' anxiety (Shishkin, et al., 1998; Kaplan and Shishkin, 2000).

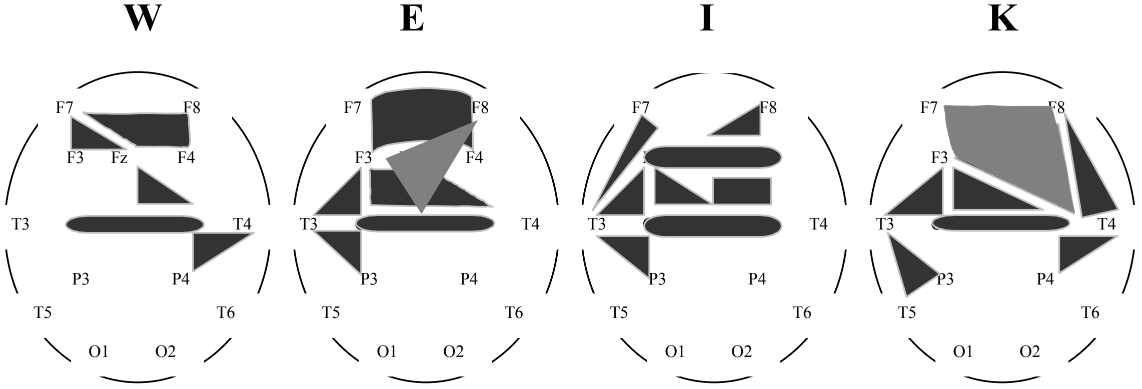

Fig. 3. An example of the operational modules' sets relevant (specific) to memory task periods, which were presented in chronological sequence: W - waiting period, E – encoding period, K – keeping-in-mind period, I - identification period. The darkened figures show the OMs.

Since the EEG signal is a mixture of different frequency components, it is possible to estimate the temporal consistency of the RTP of individual basic frequency components within the same *local* EEG (Fig. 4). It is worth to note that there are no restrictions for the relations between frequency bands, because the analysis we used is not associated with the phase relation as the usual techniques (Kaplan and Shishkin, 2000). The level of RTP synchronization in many of the pairs of the standard EEG frequency bands, both in the cases when they were taken from same EEG channel or from different channels, significantly exceeded the stochastic level (Kaplan et al., 1988). It has been shown that the index of operational synchrony of the basic EEG rhythms (IOSBR) is sensitive to the differences among various stages of the memory task (encoding, retrieval, keeping-in-mind, identification) and these differences do not depend on the frequency band neighborhood in the EEG spectral pattern (Fingelkurts, 1998). This means that IOSBR wasn't higher, for example, in the pair alpha1-alpha2 frequency bands (neighbors) if comparing with the pair delta-beta1 frequency bands (non-neighbors). The principal finding is that the OS of basic EEG rhythms (*local OS process*) decreased with the increase of cognitive loading. This dependence is opposite to OM diversity (*global OS process*) which increased along with task complexity (Fingelkurts, 1998; Fingelkurts et al., in preparation). Observed findings provide strong support for the assertion that "nonrandom neuronal activity, relatively independent of any dedicated set of neurons in some particular brain region, is how the brain trades information" (John, 2001, p. 194). These results show that the multivariability of neuronal networks is confined by the mutual dynamics of the short-term local and global metastable brain states, which maintain unity even if its composition is constantly changing (Tononi and Edelman, 1998).

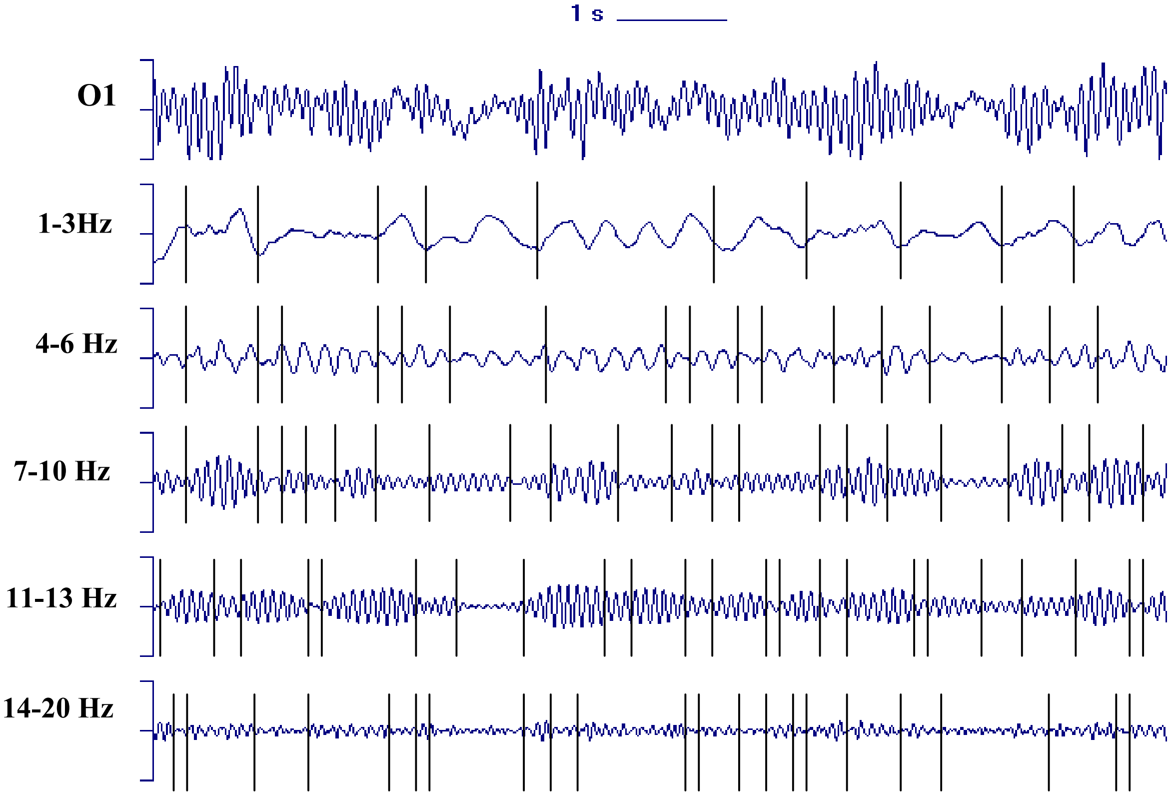

Fig. 4. An example of RTP in basic frequency bands within the same EEG channel. Note that there is some sort of RTP synchronization between different oscillations within the same EEG signal.

7. Conceptual framework of neuronal networks multivariability and metastable brain states

7.1. MULTIVARIABILITY

The concept of neuronal networks multivariability and brain states metastability is based on experimental work in which it is shown that a crucial aspect of any cognitive function is a huge multivariability of neuronal networks, which can simultaneously integrate and segregate the activities of multiple distributed cortical areas. The brain substrate in which the excitations emerge and the way they are distributed is very diverse: more then 100 billion of neurons, all these must be multiplied by 5-10 thousand of synapses on each neuron and once more multiplied by tens of operational structures in each synapse (Kaplan and Shishkin, 2000). Moreover, the cerebral cortex is highly interconnected (Felleman and Van Essen, 1991; Llinas et al., 1994). This provides evidence that activity in any cortical area might potentially be coordinated with activity in other connected areas (Bressler and Kelso, 2001). This is the “elementary basis”, which creates a very high number of combinations of possible brain states.

We will mainly follow the ideas of Kaplan (Kaplan and Shishkin, 2000) on these issues. At first glance, the basic physiological concept of homeostatic regulation of processes in living organisms appears to provide the best explanation of the multivariability of the brain (Davis and Bezprovanny, 2001). However, one must take into consideration that the idea of homeostasis contains within the hypothesis of an uninterrupted character of neuro-dynamic processes. This hypothesis supposes that the potential multivariability of neuron nets permits the brain to “organize” its activity through a practically uninterrupted and absolutely plastic tuning of its functional state according to the needs of the organism and to factors of the external environment (Davis and Goodman, 1998; Davis and Bezprovanny, 2001).

Obviously, this hypothesis is more appropriate for the description of adaptive regulation following disturbances (Turrigiano, 1999). At the same time, this concept can’t explain the active search for new “manager” decisions (Kaplan and Shishkin, 2000). Considerable evidence exists suggesting that the tasks of real management of organism functions demand a substantial limitation of degrees freedom on all levels of brain hierarchy (Kaplan, 1998). In the most pronounced manner this phenomenon exists, for instance, in the management of visual pattern recognition (Gazzaniga, 1995; Grossberg, 2000), where different visual cortical areas provide complementary constraints of visual scenes. The same effect exists in motor coordination, which is controlled by distributed motor cortical areas (Burnod et al., 1999; Chafee and Goldman-Rakic, 2000); in sensorimotor integration (Wise et al., 1997); and language and lexical comprehension (Elman and McClelland, 1984; Jackendoff, 1994).

The phenomenon of the limitation of the degrees of freedom achieves the highest tension during the realization of brain activity, hidden to the external observer, i.e., cognitive and reflective activity (Alexandrov, 1999). This workload allocates the highest number of the neuronal systems in the situation when clear signs for tuning (such as the level of glucose or blood flow) are absent (Kaplan and Shishkin, 2000). We believe, following Kaplan, that solving this problem in the framework of the continuum scheme of brain processes is incredibly difficult (Kaplan and Shishkin, 2000).

7.2. METASTABILITY

At the same time, the logic of available experimental data and theoretical considerations suggests that cortical areas separately are characterized by different characteristic spatial and temporal parameters (Bressler, 1987a,b; Fingelkurts Al., 1998). Accordingly, these areas have the ability to realize definite operations' sequence in the time unit. Therefore, the sufficient coordination of the activity of such cortical areas integration is reached to the extent that cortical areas are able to mutually influence each other in order to reach a common functional state, stabilizing its main parameters. It is likely that optimal informational processing is possible only under the functional stabilization of intercortex relations (Kaplan, 1998; Fingelkurts and Fingelkurts, 2001). These relations may be imagined as a mosaic of simultaneously coexisting (yet with different beginning and end points) different local and global cortical networks dynamics, which execute the realization of definite nervous activity macrooperations (Fingelkurts An., 1998, Fingelkurts Al., 1998; Kaplan and Shishkin, 2000; Fingelkurts and Fingelkurts, 2001).

The life-span of such specific operational modules (OM) is determined by the duration period of the mutual stabilization of the main parameters of neuron networks involved. At the EEG level this is reflected in the stabilization of the quasi-stationary segments on corresponding EEG sites. Here it is important to emphasize that the structural EEG organization is a hierarchy of segmental descriptions on different time scales (for details see Kaplan and Shishkin, 2000). This is mean that EEG contains segments with different time duration on different time scales what is reflected in the life-span of metastable states. One can note the correspondence between OM described in the present work and the functional clusters of Tononi et al (1998). Pribram (1991) called the spatiotemporal patterns of cooperative processes as holoscapes. Nunez speaks about 'quasi-stable spatial structures' (Nunez, 2000). Although all these modules have much in common, the differences between them come from the particular method of their estimation. We do not think that OMs are directly connected with the structural modules of the cortex (Szentagothai, 1978). We also emphasize that discussed OMs are distant from static functional modules (FM), where each function is allocated to a element of system – FM, and features of external stimuli are directly mapped to each FM. Our OMs have dynamic behavior – they are metastable. So the function of each element cannot be uniquely determined (Tsuda, 2001). This is in line with work of Ramachandran (1998), who found evidence of considerable changes of FM, what is in agreement with the concept of a dynamic brain (Erdi, 2000). Metastable states which are proposed in this work are the brain field property and might offer some advantages over physical connections, as considered briefly in Nunez (2000) and in the work of Hoppenstead and Izhikevich (1999), who found that the synaptic connections between cortical columns did not guarantee substantial interactions. In resent publication, John (2001) also argue that brain electromagnetic field might be those phenomenon where we must search an emergent property of mentality.

Thus, that *metastability* (when the system's degrees of freedom are restricted) is circumstantial for the interaction among the elementary neuronal systems: by synchronizing the stable microstates of the "microscopic variables" during certain period, the neuronal systems have the possibility for *interactive information exchange* of the essential variables, which are important for the acceptance of "agreement decision" (Kaplan and Shishkin, 2000).

In this interpretation, the "transition" of the same cortical area into the new OM, in accordance with participation in the realization of another functional program, must depend on the ability of this area to adapt to the main variables of the new OM. Here it is important to stress that discrete parts of the cortical networks may gain another functional meaning when they are recruited by other OM and, therefore take part in realization of another functional act (Fingelkurts, 1998; Fingelkurts and Fingelkurts, 2001). This confirms the dominant principle of the nervous constellation centers formed by Uhtomskyi, who discussed the variable functional role of different brain cortical areas depending on their participation in various working constellation (Uhtomskyi, 1978). This viewpoint is also in line with recent theoretical works concerning cortical coordination dynamics (Erdi, 2000; Bressler and Kelso, 2001).

Hence, empirical evidence suggests that every functional state includes elements, which are sufficient for the past (basis for memory), present and future. During the process of a program's realization the dynamic state replacement takes place so that specific elements of the past become unactualized, the elements of the present become the past and the elements of the future become the present (see Fig. 2, 3). Thus, it is possible to make the critical supposition that an individual experience reflects the world with anticipation (Alexandrov, 1999). Individual activity in each given moment is not just a reaction to a past event, but a preparation and realization of the future (Heisenberg, 1994; Shvirkov, 1995; Alexandrov, 1999).

7.3. SELF-ORGANIZING PROCESS

Such coordinating or operational consistency is the result of a *self-organizing* process and does not require any supplementary or special “coordinate” center (Erdi and Barna, 1984; Edelman, 1989; Fingelkurts, 1998; Nanez, 2000; Erdi, 2000). Framing the question in this way, it shows that operational consistency of functional acts occurs by necessity, from the impossibility to simultaneously execute the numerous programs needed, in limited space and time (Fingelkurts, 1998). This viewpoint is in good agreement with Prigogine’s concept of so-called dissipative structures arising from chaos based on the principle of self-organization (Prigogine and Stengers, 1986). Correspondingly, the interaction of the cortical areas may appear on the base of the self-organization of neuronal groups with different parameters during the concrete activity (Erdi and Barna, 1984; Kelso, 1995; Haken, 1996; Bressler and Kelso, 2001), forming the corresponding mental functional state (Ivanitsky, 1997).

In that sense, the operating principle of the brain activity is a hierarchic synthesis of information with the parallel ultimate generation of entropy (Khazen, 1992). We review this evidence in the light of the joint action (Khazen, 1993, 1998, 2000) of the *Second Law of Thermodynamics* and the *Principle of Maximum Entropy Production* (Ultimate Metamorphosis Capability). Khazen showed in his works that self-organization leads to the mutual increase of entropy and information synthesis (Khazen, 1993, 1998).

The dynamic of the self-organization process is as follows. The state of the minimum of entropy is *statistically* unstable. This permits further increase of the entropy – self-organizing process. During this process the entropy production starts to fit the Lyapunov criteria (Khazen, 2000), and the state becomes dynamically stable. This metastability provides the information synthesis along with *Maximum Entropy Production* and establishes the conditions for memorizing (Khazen, 1993, 1998). In physics 'stability' is synonymous with 'memorizing' (Khazen, 1998), meaning that something possible to be repeated or reproduced.

By definition, metastability means the sequence of the stable states (Kelso, 1995; Bressler and Kelso, 2001). In each of these states Prigogin's *Principle of Minimum Entropy Production* is locally executed (Prigogine and Stengers, 1986). However, new conditions (environment) always change rapidly, leading to new random events causing a breakdown of the stable state, which is characterized by a minimum of entropy. Thus, the whole cycle repeats itself (Fig. 5).

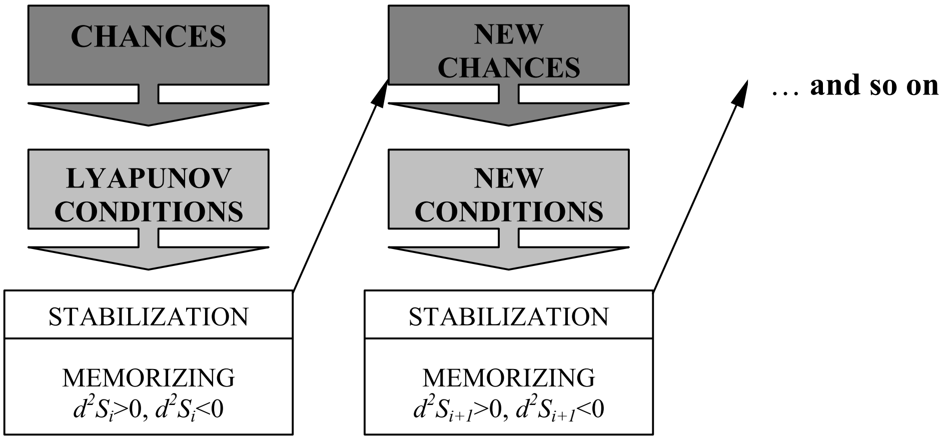

Fig. 5. The dynamics of the self-organizing process (modified from Khazen, 2000).
Legend: d^2S_i – entropy/information increasment

One can see that this universal law of 'Ultimate Metamorphosis Capability' (Khazen, 1992, 1993, 1998, 2000) is applicable to the brain information processing (in terms of operational synchrony). Through the process of the operational synchrony (OS), the cortical system has the possibility to perform many operations (functions) using one or more metastable operational modules (OM) of coordinated networks at a given stage of processing; then along with the transition to another stage, rapidly shift to another metastable OM(s) (Fingelkurts, 1998; Fingelkurts and Fingelkurts, 2001). Thus, the potential multivariability of the neuronal networks appears to be far from continuous in time, but confined by the dynamics of short-term local and global metastable brain states (Kaplan and Shishkin, 2000, Fingelkurts and Fingelkurts, 2001). In the framework of this interpretation, the *global OS process* (operational modules of cortical areas) creates a 'context' for the *local OS processes* (interfrequency consistency in local cortical areas). The dynamic creation of the local context is a way for the brain to function in a highly productive manner (Bressler and Kelso, 2001). Re-entrant transmissions among the cortical areas (Edelman, 1989; Sporns, 1989) may be the neuronal basis for such cortical integration (Tononi et al, 1992, 1998).

However, one can see here some parallels with attractor networks that exhibit similar behavior (Singer, personal communication). For the detailed description of stochastic *versus* nonlinear deterministic methodology and their applications to EEG research see recent review by Fell et al. (2000). It is an unresolved problem in nonlinear EEG research that nonlinear methods *per se* give no feedback about the stationary aspect.

8. Parallels in the dynamic structure of the different brain levels' organization, cognitive and behavioral acts

Although all our research focuses on the cortical level, which is practically relevant to cognition (Nunez, 2000; Bressler and Kelso, 2001), it is evident – following Revonsuo (1999), who proposed the idea of different binding levels – that the concept of operational synchrony may be extrapolated to other brain levels and to cognitive and behavioral levels.

8.1. MOLECULAR LEVEL OF THE CELL (NEURON)

During the past three decades, new understanding of cellular processes and particularly metabolism has developed (Heinrich and Rapoport, 1974; Kacser et al., 1995) into ‘biochemical system theory’ (Alves and Savageau, 2000). According to this framework, the multivariability of thousands of enzymes and other molecular substances that might interact with other enzymes through intermediates affecting their rates, can be solved only by binding local operational acts in steady state – multi-level reaction networks (Hofmeyr and Westerhoff, 2001) or in assembled metabolic networks (Mittenthal et al., 2001), which change rapidly along a cascade of processes (Alves and Savageau, 2000). The analogy with introduced above brain operations, integrated by means of the operational synchrony process in local and global operational modules, is obvious.

8.2. THE LEVEL OF SINGLE NEURONS

It is well documented that neurons in both cortical and subcortical centers can synchronize their activity with a precision in the millisecond range (Gray and Singer, 1989; Engel et al., 1997, 1999; Singer et al., 1997; Singer, 1999; Wright et al., 2000). It has been shown both for the cortical areas (visual, motor, sensory) and for subcortical systems that synchrony can be internally generated (non-stimulus-locked) and externally induced (stimulus-locked) (Engel et al., 1999). Although some authors supposed that the role of coincidence detector is played by the synapse (Kalitzin et al., 2000), it is obvious that backpropagating spikes and active dendritic responses also play an important role (Singer, personal communication).

If the pre- and post-synaptic neurons are activated coherently, then the synapse can reach its maximum efficiency state. Long-term potentiation (LTP) is a phenomenon connected with a stable increase in the efficiency of the neural synapse (Bliss and Collingridge, 1993). N-methyl-D-aspartate (NMDA) plays the main role in this process (Artola and Singer, 1993). This process on the whole represents a Hebbian learning rule – increases in synaptic strength between neurons that fire together (Hebb, 1949; Buonomano and Merzenich, 1998). The new asymmetric Hebbian rule provides an immediate mechanism for self-normalization of synaptic weights (Kempter et al., 2001; Senn et al., 2001; Bi and Poo, 2001). Also the famous Hodgkin-Huxley (HH) equations (Hodgkin-Huxley, 1952) and modified HH equations have been proposed as a prototypical neuron model exhibiting a variety of dynamics (Doi et al., 2001). Although, it is not the goal of the current article to address this large and growing field in detail, we stress that in these studies it has been shown that operational activity of single neurons is synchronized in steady-state assemblies depending on current global activity (Sturm and König, 2001).

8.3. THE LEVEL OF CORTICAL AND BEHAVIORAL ACTIVITY

We strongly believe that the level of large-scale cortical networks (not the level of single neurons) is most relevant to cognitive functions, and is in agreement with current concepts (Nunez, 2000; Bresler and Kelso, 2001; Zeki, 2001; Revonsuo, 2001, John, 2001). This level of brain organization has been described above (subsection 7). In the context we consider, it is plausible to show the correspondence between concept of the operational structure of the biopotential brain field and the structure of behavioral/cognitive activity.

Empirical evidence suggests that systemic mechanisms compose the operational architecture of any functional system (Anokhin, 1973; Alexandrov, 1997). From this viewpoint it is believed that the behavioral or cognitive continuum is the succession of *discrete* behavioral/cognitive acts performed by an individual during his/her life (Alexandrov, 1999; Helekar, 1999). Each separate act is the integration of a certain number of operations, which are important and appropriate for realization of this act. During this *operation's binding,* the redundant degrees of freedom are eliminated, thus the "decision" of what should be done and how to achieve the adaptive result is made (Alexandrov, 1999). Therefore, each of these acts is fixed on a certain stage of development of the given behavior/cognition (element of individual experience) (Alexandrov, 1999, Helekar, 1999). These fixed states form the conditions for learning (Edelman, 1987) and/or memorizing (Grechenko, 1991).

The change from one behavioral/cognitive act to another is reflected in *transitional processes* which play the principal role in the organization of behavior/cognition. During transitional process the comparison with the parameters of the final result reveals the correspondence between the achieved 'goal' and the 'goal' that was planned (Alexandrov, 1999). The Fig. 6A illustrates the behavioral/cognitive continuum. One can see, that the description of the behavior/cognitive continuum as a chain of the discrete acts (the results of which are achieved due to the simultaneous realization of certain number of operations) coincides completely with the description of the operational architectonics of the biopotential brain field proposed in the present paper (see Fig. 6 A, B).

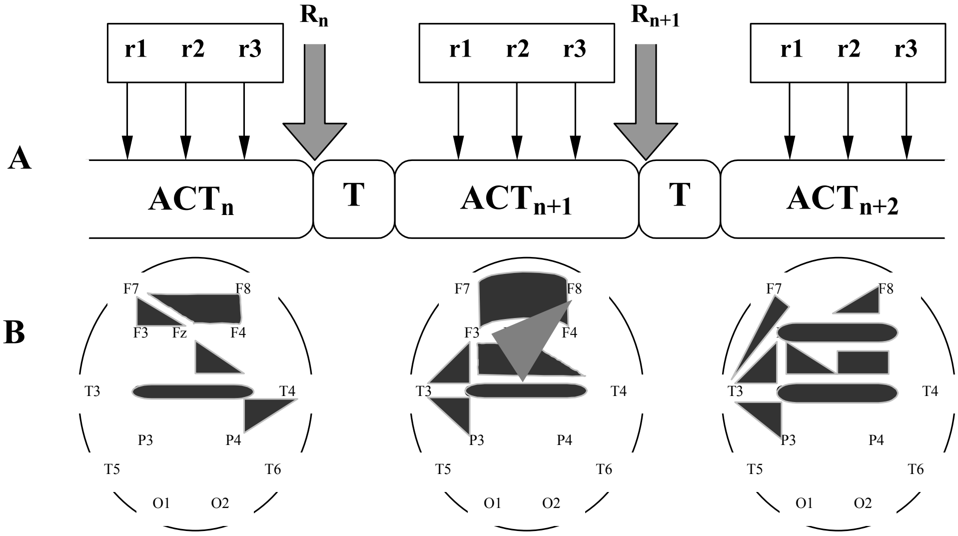

Fig. 6. The shematic illustration of the behavioral/cognitive continuum (*A* modified from Alexandrov, 1999).
Legend: *A* illustrates the behavioral/cognitive continuum; *r1, r2, r3* – subresults, R_n, R_{n+1} – results of behavioral/cognitive act, *T* – transitional processes. *B* – the sets of operational modules (OM) that subserve the realization of the successive acts in the continuum. Each OM subserves the realization of the subtasks by binding together the certain number of operations going on in diferent cortical areas. Note that in the transition, cortical system rapidly breaks functional couplings within one set of areas and establishes new couplings within another set.

In this conceptual framework, mental states emerge from the metastable operational modules found in the process of operational synchronization of elementary operations. Therefore, physical ('objective') and mental ('subjective') processes in this line are considered as two basic and complementary aspects of the same whole informational brain state. In this sense it is possible to come closer to understanding how something subjective has causal interactions with something objective. Moreover, introduced in present article framework allows to reveal "[…] the fact that there is a phenomenal world being constructed in the brain" (Revonsuo, 2001, p. 9).

9. The Operational Architectonics' Concept and phenomenal consciousness (speculative remarks)

It is very appealing, based on empirical work, to link the *structure* of the operational architectonics of the human brain biopotential field with the *phenomenological structure* of human consciousness. However, here a central dilemma arises: the concept of the operational architectonics, which specifies how mental states emerge, seems not to need consciousness for it functioning. So, the mere existence of the operational synchrony (OS) is necessary but not enough for consciousness emergence. This is evidenced by the finding that the OS process is present in the brain even during waking (stimulus independent) activity (Fingelkurts, 1998; Fingelkurts et al., 1998, 2000), also highly possible in all sleep stages (Kaplan et al., 1997a) and exists in epileptic states of absence (Fingelkurts, unpublished). Common sense suggests that OS process continues to occur in the absence of subjective awareness. At least at the level of single neurons it has been shown that the synchronization exists in anesthetized animals (Ts'o, 1988) and a "high-level synchrony also goes along with a loss of consciousness" (Baars, 2001, p. 162). So, most likely operational synchrony provides a satisfactory explanation to the emergence of the nonconscious mental states, which operates not only in humans but also in animals.

We try to be far from confounded the correlation and ontology. To avoid confusion in further discussion, it is important to stress that we do not attempt to explain how consciousness arises from neuronal tissue. Instead, we demonstrate that the phenomenological structure of consciousness corresponds to the structure of the operational architectonics of the human brain biopotential field, described in the present work.

William James did the most fecund and detailed (but metaphorical) phenomenological description of the structure of human consciousness in his 'Stream of

Though' theory (James, 1890). His main observation that consciousness is dynamic where it continually moves from thought to thought is currently being developed by various authors (Mangan, 1993a, b; Chafe, 1994; Galin, 1994, 2000). We use this concept as a basis for further discussion, because it is the classical (and canonical) one and represents a phenomenological description of the structure of human consciousness. Indeed, the description of consciousness should be made not in terms of neuronal correlates of consciousness (NCC), but in terms of the actual subjective phenomenology of consciousness (Revonsuo, 2001). That is why it is so important to show the correspondence between experimental (neurophysiological) data and some of the features of the phenomenal level (consciousness).

To our knowledge of the literature, Epstein has been the first to make a serious attempt at applying James' ideas to the field of neurology (Epstein, 2000). However, he, like most neuroscientists, examines only the neural and cognitive correlates of consciousness phenomenology. But this approach has some limitations (Searle, 1980, 1997, 2000; Revonsuo, 2001). Neuropsychological literature (Pribram, 1991; Gazzaniga, 1998; Corkin et al., 1997; Teng and Squire, 1999) and animal experiments (Squire, 1992; Suzuki et al., 1993; Buney and Eichenbaum, 1996; Burton et al., 2000) have established that the same brain formations and cortical areas may participate in numerous functions and different mental states (Fingelkurts et al., 1998, 2000; Fingelkurts et al., in preparation). Furthermore, the brain basis for consciousness *must* be distinct from related constructs like selective attention, working memory, sensory knowledge and executive control (Baars et al., 2000).

Taking all these into consideration we try to show epistemic *correspondence* of the two structures, – the structure of the operational architectonics of the biopotential human brain field and the structure of human phenomenological consciousness, but not to show the *correlations* between concrete brain formation(s) and consciousness state(s).

First, let's consider the James' metaphor of a kaleidoscope (James, 1890, p. 246). Using this metaphor James illustrates the ever-changing stream of thoughts like a rotating kaleidoscope where each momentarily stable pattern is a thought. Similarly, consciousness is always changing, but it presents us with a series of substantive thoughts that are themselves momentarily stable. Thus, James considered that consciousness has a composite structure: it contains *stable* nuclei (or images) and *transitive* fringes (or periods).

The primary features of James' phenomenology of stable images are:

1) relative *stability*,
2) *memorability:* one is more likely to remember the stable images/thoughts than transitive parts (Epstein, 2000);
3) *multimodality:* they include except others verbal, visual, attitudinal representations and even meanings (Epstein, 2000);
4) they appear *sequentially:* it is possible to have only one subjective experience/image at a time (Mangan, 1993a; Tononi and Edelman, 1998), and
5) they have a *limited capacity:* only a small proportion of the total amount of information processed by the brain can be presented in any one stable thought/image (Mangan, 1991, 1993a).

It is evident that all these features are simultaneously phenomenological and functional (Epstein, 2000). One can see the remarkable correspondence between these characteristics of stable thoughts/images and the features of multistable operational modulus (OM) which are (Fingelkurts, 1998):

1) *multistable:* it is combination of a certain number of stable discrete operations;
2) *memorable:* stability opens the 'room' for memorizing (see above);
3) *multimodal:* integration of operational work of different brain areas, which operate different modalities;

4) they may appear *sequentially* and
5) have a *limited capacity:* redundant degrees of freedom are eliminated (see above).

Another James' construct is transitive periods or fringe. In his conception these transitive periods provide a sense of context that bridges the rapid temporal gaps between stable thoughts/images (Epstein, 2000). The main features of transitive periods are: filings of *context* (filing of 'on-the-tip-of-the-tongue'), connection with the current *goal* (feeling of 'on-the-right-trackness', see also Alexandrov, 1999), connection with *cognitive emotions* (Mangan, 1993a; Galin 1994), connection with the *memory* about previous stable thoughts/images. Similarly, in operational architectonics' concept the short-term metastable states are changed rapidly during transitive periods (Fingelkurts, 1998; Fingelkurts et al., 1998, 2000; Fingelkurts et al., in preparation).

Thus, it is evident that James' kaleidoscope metaphor precisely describes not only the structure of phenomenological consciousness but also the structure of operational architectonics of the biopotential human brain field. This suggests that consciousness has a structure that can be now investigated not only through phenomenology but also through neurophysiological experimentation. Moreover, it is possible that if the phenomenological structure of consciousness and the structure of the brain's operational architectonics are so remarkably correspondent to each other, then they might have ontological identity.

Here we permit ourselves to make some *speculative* remarks about consciousness emergence. We hypothesize that all mental states are divided into several groups. Some of mental states are potentially conscious (Searle, 1997) or pre-conscious. Other mental states are ex-conscious (conscious experiences which become unconscious). Although, both pre- and ex-conscious mental states are 'raw' images that have not been actualized in a given moment, their grouping together into certain *complexities* might lead to conscious awareness. We hypothesize that a certain relationship (leading by unconscious associative process, Dulany, 2000) among several mental states makes it possible for subject *to be fully conscious of something* in the sense of our particular first person's point of view (Trujillo, 2000; Perruchet and Vinter, 2000). The question that emerges then is: what is this *certain* relationship? Possibly, the binding mechanism of 'raw' mental states together is *semantic-conceptual* coupling (Revonsuo, 1999) in which, as we think, natural language plays an important role. As a subject can name this mental complex-object it is immediately possible to attend to this 'object' as some kind of meaningful entity and to access "an enormous amount of information about that kind of object" (Revonsuo, 1999, p. 179). This is how categories, symbols and ideals are formed (Dulany, 2000) and how the subject is made "independent of the particular to which it would otherwise be enslaved" (Zeki, 2001, p. 69). Thus, according to Koriat "consciousness can be said to bind together knowledge and meta-knowledge" (Koriat, 2000, p.150). This metacognition not only enhances the subject's sense of control (Koriat, 2000) but also contributes to a subjective sense of predictability of a desired outcome (Graham and Neisser, 2000). Here we need to stress, that we are not against the fact that activation in the conceptual-semantic system of the brain can occur even in the absence of conscious understanding of stimulus meaning (Revonsuo, personal communication). Activation of this system and conceptual-semantic coupling of mental states are two different claims. Although 'raw' mental states may exist in animals, we believe that in animals the semantic-conceptual relations are strongly limited by biological vital needs. As a result, animals' brains can't solve tasks over a longer time scale independent of external sensory stimulation (Binder et al., 1999). Further we need conclude that the most crucial level of organization for consciousness studies, the phenomenal level, remains seriously inaccessible in animals (Revonsuo, 2000a). The importance of the postulated special relations between mental states will be examined below.

We propose another group of mental states that are always unconscious, to which the subject can never gain conscious access during his/her life. Nevertheless, these unconscious states relate somehow to 'raw' mental states and may influence or modulate the resulting construction of each conscious state (Kelly and Jacoby, 1998; Whittlesea, et al., 1990) or influence behavior directly (Dijksterhuis et al., 1998). See Bargh (1997) for a discussion about numerous affects of unconscious processes on a variety of judgments. Some evidence comes from effects which occur in posthypnotic actions (Hilgard, 1965) "when people are induced to execute goal-oriented actions that they did not consciously choose and without being aware of the reasons for their behavior" (Koriat, 2000, p. 154). This viewpoint is to some extent in line with Llinas and his colleagues according to whom consciousness is modulated rather than created by the sensory inputs (Llinas, 1990; Llinas et al., 1998). This means that perceptual experience is based on an unconscious inference from a variety of cues (Palmer, 1999; Koriat and Levy-Sadot, 2000). We believe that nonconscious mental states and their relations with 'raw' mental states are present both in humans and animals.

The essential concept is the transitional point when conscious and unconscious states (thoughts) change. We hypothesize that at this point the 'stream of thought' can change its direction in *n*-dimensional mental space or virtual reality. These points are just those "places" where the subject may be partially or fully aware about the existence of the previous thought(s) and voluntarily shift his/her attention or direction of thinking. This view occurs with the position of Koriat, who suggested that metacognitive feelings "play the role of a go-between, allowing a transition between an implicit-uncontrolled mode of operation and an explicit and relatively controlled mode" (Koriat, 2000, p. 163). The 'bizarreness of dreams' (e.g., incongruity, discontinuity) (Hobson, 1988; Revonsuo and Salmivalli, 1995) prove that in waking (unsleeping) consciousness the binding of mental images at transitional points is quite different from the binding that occurs during sleep, thereby providing evidence of the importance of transitional periods in the construction of conscious awareness (Revonsuo, 2000a). This concept is supported by tip-of-the-tongue (TOT) and feeling-of-knowing (FOK) phenomena. In FOK and TOT experiences, a neighboring target activated from a memory entry other than the correct one (Koriat and Levy-Sadot, 2000), suggesting that the 'normal' interplay between mental images is broken. Further evidence of the importance of relations between mental states is provided by psychiatric patients. Individuals experiencing the thought disorder known as thought-insertion have strong beliefs about their own thoughts, but attribute their thinking to aliens (Stephens and Graham, 2000). Clearly much work is needed to clarify the precise relationships between mental images/thoughts. The understanding of these relations help us to realize how phenomenal consciousness could arise or be wholly constituted by nonconscious processes.

Thus, one can see in the result of this theoretical work that consciousness is a certain brain state (Searle, 2000) that results from certain relations between different 'raw' and unconscious mental states, which in their turn emerge in the result of brain operational processes.

However, the main question remains unanswered: does introspection *report* our mental states or *interpret* them (Rosenthal, 2000)?

In concluding, it is emphasized that the present work is not intended to be the final word. It outlines several testable predictions. If these predictions turn out to be correct, than presented hypothesis receives considerable support, but if they turn out to be false, then the theory either must be rejected or at least thoroughly modified.

10. Summary and conclusions

According to Luria (1980), a complex function is a system of interrelated processes (operations) which is directed toward the execution of a particular aim. A network of functionally related cortical areas implements this complex function neurally (Luria, 1980). Thus, the large-scale level of cortical networks is seen as the most essential for the coordinated transfer of multimodal cortical information underlying cognition (Bressler and Kelso, 2001) and consciousness (Revonsuo, 2001; John, 2001). The present paper introduces the concept of the brain *operational architectonics* as a unified framework to show how the spatial and temporal hierarchy of discrete metastable states of neuronal nets can serve in real time as a basis for brain functioning in rapidly and unpredictably changing environments.

The hierarchy of EEG segmental description on different time scales (Kaplan and Shishkin, 2000) suggests that operational process takes place at various time scales and thus, can be executed in any EEG frequency band (Fingelkurts, 1998). In this sense, inter-area operational synchronization may occur not only in gamma-frequency oscillations, thereby providing evidence that awareness must not necessary be linked with 40Hz synchronization. Moreover, "[…] simple electrical stimulation of isolated invertebrate ganglia evokes gamma oscillations (in the absence of perceptual binding or higher cognitive processes)" (Basar et al., 2001, p. 244). These findings suggest that integrative functions, behavioral and cognitive acts, and even consciousness may be supplied by operational synchrony which takes place simultaneously in different frequency oscillations at both local and global levels. Thus, the brain operates by maintaining a balance between its integrative and segregative functions.

Interestingly, the processing of information on the basis of operational synchrony seems to proceed concurrently at multiple levels: metabolic, single neurons, neuronal nets and between brain areas. It also underlies cognitive and behavioral acts. This suggests that operational synchrony may be a general basic biological phenomenon, providing a unified methodological and conceptual basis for future multidisciplinary research.

It is hypothesized that the process of operational synchrony leads to the emergence of nonconscious and 'raw' mental images, which exist in both humans and animals. The semantic-conceptual binding (Revonsuo, 1999) of these mental images may cause awareness and full consciousness in those cases when subject can name the result of such images' binding. We believe that this process at full extent functions only in humans' brain. Thus, it was shown that operational architecture of biopotential brain field can be that natural (physical) phenomenon, which could realize the kind of structure, and dynamics as is found at the level of phenomenal experience.

10.1. SOME IMPLICATIONS FOR FUTURE RESEARCH

Knowledge of the operational architectonics of the biopotential field may be very useful for research of the artificial intelligence and the neurocomputer creation. It is believed that a new generation of computers will employ principles of the human brain (Hoppensteadt and Ishikevich, 1999). There are many neural network models that can be used as a theoretical basis for a neurocomputer (for the review see Arbib, 1995). However, we believe that the most promising models are those which take into account the operational architectonics of the biopotential brain field, where the distributed neuronal system can reach self-metastable state(s) (Fingelkurts and Fingelkurts, 2001). The advantages of such system are: a) enormous reduction of computational time, b) higher efficiency with balanced workload, c) rapid selection from vast number of possible networks the one, which is the most relevant to a particular task (reduction of uncertainty) and d) avoiding the state explosion problem.

These properties are very useful in distributed environments where no centralized control exists. Neurocomputers and artificial neural networks are examples of such environment. However, the problem with the majority of current artificial networks is that they typically settle into a stable state and stay there (Bressler and Kelso, 2001). In other words, they became locked. We believe that this and other problems can be avoided by implementing the principle of operational synchrony in IT technologies (Fingelkurts and Fingelkurts, 2001).

Appendix 1. Disadvantages of EEG segmentation methods

Segmentation with fixed windows has a serious disadvantage: some of the fixed intervals should necessary fall on boundaries between the *real* stationary EEG segments. This leads to the appearance of a variety of EEG fragments which contain transitional processes and, hence are not strictly stationary.

Parametric EEG segmentation methods operate with *empirically* chosen threshold criteria. This makes it difficult to compare the results of segmentation not only from different subjects, but also even from different EEG channels in the same subject. Lacking of *a priori* knowledge about the law of variations of model parameters, it is necessary to construct additional models, which should result in greater error.

In principle, all parametric methods designed for the analysis of nonstationary processes are based on a procedure which may be applied *only* to stationary processes, namely on fitting a mathematical model (usually the autoregressive one). Thus, a huge contradiction exists: segmentation into stationary fragments is impossible without construction of an adequate mathematical model, but such a model cannot be built without previous segmentation. For details see Kaplan and Shishkin, 2000.

References

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Appendix 2. New nonparametric adaptive EEG segmentation

The EEG signal is nonstationary: it has different statistical characteristics at different time intervals (Brodsky et al., 1999); or it can be considered as a piecewise stationary process, i.e. as a process “glued” from several stationary processes with different probabilistic characteristics. It is well established that the complete description of a random process, in general, is represented by the total set of its finite-dimensional distributions, which are invariant with respect to time shifts for strictly stationary processes (Fell et al., 2000). Usually stationary processes, which are components of a glued process, differ in their distribution functions. The places of “gluing” then are the moments of changes of statistical characteristics or, more precisely, rapid transitional periods (RTP) (Kaplan and Shishkin, 2000). For a strictly stationary process any statistical characteristic does not depend on time, hence, moments of RTP in the piecewise stationary scheme are determined by moments of gluing (Fell et al., 2000). Thus, the task is to divide the EEG signal into stationary segments by estimating the points of “gluing”.

The principle of originally designed technology of adaptive level segmentation is the moving double screening of EEG. The main idea is in comparison between ongoing EEG absolute values averaged in *test* window (13 points=101 ms) and EEG absolute values averaged in *level* window (120 points=937 ms). This technology (realized in program “SECTION”, developed in Moscow State University) is based on the automatic selection of level-conditions in accordance with a given level of the probability of “false alerts” and carrying out simultaneous screening of multi-channel EEG. If the absolute maximum of the averaged values in the test window is less or equal to the averaged values in the level window, then the hypothesis of EEG homogeneity is accepted. Otherwise, if the absolute maximum of the averaged values in the test window exceeds the averaged values in the level window, according to the threshold of the false alerts (the Student criteria, $p < 0.05$ with coefficient 0.3), its time instant becomes the preliminary estimate of a RTP. Also another condition must be fulfilled in order to eliminate possible anomalous pecks in amplitude: the five points of EEG following this preliminary RTP must have statistically significant difference between averaged values in test and level windows (Student criteria, $p < 0.05$ with coefficient 0.1). If these two criteria are met, then the preliminary RTP are assumed as actual. Then each of windows shifts on one point from actual RTP and procedure is repeated. Details about this and others segmentational procedures can be found in our previous publications (Fingelkurts, 1998; Brodsky et al., 1999; Kaplan and Shishkin, 2000).

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Appendix 3. The Operational Synchrony technology.

The aim is to estimate the synchronization of rapid transition processes (RTP). This approach can reveal functional interrelationships of cortical areas different from those measured by correlation and coherence analysis. Each RTP in the *reference* EEG channel (the channel with minimal number of RTP from each pair of channels) was surrounded by a "window" (from –3 to +4 points to each side from RTP point) of 63 ms and all RTP from another (*test*) channel were thought to be coinciding if falling into this window. The window of 63 ms provides the 70-80% of all RTP synchronization. On the basis of this procedure, the estimation of the index of operational synchrony (IOS) for pairs of channels or searching for the most frequent multichannel combinations (operational modules) can be made. Several algorithms and methodology of RTP synchronization are described elsewhere (Kaplan et al., 1997; Fingelkurts, 1998; Kaplan and Shishkin, 2000). This technology, named “JUMPSYN”, was developed in Moscow State University. Here we only note that the IOS was computed as follows:

$$\mathrm{IOS} = m_{windows} - m_{residual}\text{, where } m_w = 100 * \frac{sn_w}{sl_w}\text{ ; } m_r = 100 * \frac{sn_r}{sl_r}\text{ ;}$$

sn_w – sum number of RTP in the windows in the test channel;

sl_w – sum length of EEG recording (in points) inside the windows in the test channel;

sn_r – sum number of RTP outside the windows in the test channel;

sl_r – sum length of EEG recording (in points) outside the windows in the test channel.

One can see that the IOS tends to zero in the case of no coupling between the RTP and takes positive values when such coupling exists.

On the basis of pairwise analysis, the OS (operational synchrony) in several channels was determined (so-called operational modules – OM). OM means that the group of the cortical areas participates in the same functional act during the analysis period. At the EEG level it is reflected in the set of EEG channels in which each channel forms a pair combination (operational synchrony) with other EEG channels of the set. However, now we are working on the creation of more precise estimation of OM. The term “order of areas recruitment” indicates the number of cortical areas recruited in OM.

It is obvious that even in the absence of any functional cortical interregional cooperation there should be a certain stochastic level of RTP coupling, which would reflect merely occasional combinations. The values of such stochastic interarea relations must be substantially lower than in the actual presence of functional interrelation between areas of EEG derivations.

For appropriate estimation of 5% level of statistical significance of IOS, the Monte Carlo modeling was held (500 independent trials). As a result of Monte Carlo tests the stochastic level of RTP coupling (IOS_{stoh}), and upper/lower thresholds of IOS_{stoh} significance were calculated. It is apparent that just these values are the estimation of the maximally (by module) possible stochastic rate of RTP coupling. Thus, only those values of IOS which exceeded the upper/lower thresholds of IOS_{stoh} have been assumed to be statistically valid.

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