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Chapter 2

MAPPING OF BRAIN OPERATIONAL ARCHITECTONICS

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ABSTRACT

Recent neuroscience is lacking of consistent theory and methods for understanding the mechanisms through which the brain orchestrate the symphony of perceptions, thoughts and actions. The aim of this Chapter is to contribute to a better understanding of such mechanisms by establishing methodological foundations of the Operational Architectonics framework of brain and mind functioning. The theory we offer provides a framework for mapping and understanding important aspects of the brain mechanisms that constitute perception, cognition, and eventually consciousness.

Keywords: EEG/MEG, Operational Synchrony, Structural Synchrony, Functional Connectivity, Neuronal Assemblies, Brain Operations, Mind, Temporal Structure, Binding, Perception, Cognition, Consciousness, Dynamical, Symbolic, Neurocomputational Approach, Isomorphism

> *<We may be able one day to use brain waves as indicators*
> *of the beginning and end of a mental process…>*
>
> Robert S. Woodworth (1938)

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INTRODUCTION

Attempts to understand systematically the brain and mind and their operations go back at least to the Ancient Greeks, when philosophers such as Plato and Aristotle tried to explain the nature of human knowledge. However, until recently such understanding is simplistic and is still a source of puzzlement. And it is so despite the fact that over last few decades there has been an explosive development of new theories regarding the brain and mind functioning and powerful techniques that allow studying it. Contemporary scientific knowledge about the brain is as follows: Simplifying, the brain is essentially a network of neurons (and glia) interconnected with synapses. Particular neurons are connected to inputs from which they receive information from the outside world. If these neurons receive a sufficiently strong signal, they fire, thereby affecting more neurons, and so on. It is supposed that neurons represent features in the input and that connections between neurons encode relational context among those features (Choe, 2002). Eventually, an output signal, acting on the outside world is generated. However, in such interpretation, the static and passive role is assigned to the brain.

In reality brain does not simply represent the environment in a different format (Erdi, 2000; Buzaki, 2004). It rather generates its own mental representations and behavior, thus been a functional active entity (Alexandrov, 1999; Freeman, 2000; Cariani, 2001)[1]. In another words, the living brain is in a state of permanent flux, been continuously in a change accordingly with its environment (external and internal). It senses the environments, anticipates what actions are appropriate (Freeman, 2000; Erdi, 2000), and acts accordingly through the sequence of operations (Alexandrov, 1999). Here the operations of perception, coordination-anticipation, and action in the organism become the measurements, predictive computations, and actions (Cariani, 2001). By probing its environment, brain extracts from the changing array of stimuli the regularities and covariances that assert the stability of the external world (Paillard, 1991). Such regularities are printed in the neural circuitry of cortical modules through the stabilization of co-activated synapses (see discussion in Phillips et al. 1984). An internal representation of a stable predictable environmental framework (system of mental states or images) thereby emerges, which gives coherence and unity to the spatial relationships that link the organism to its external world. In such a way, brain, been a complex system, achieves a degree of epistemic autonomy relative to its surrounds (see also Cariani, 1994; Erdi, 2000).

It is obvious, that both brain and mind functioning have a *temporal structure* (Pöppel, 1988; Glicksohn, 2001). The time range for complex brain-mind operation is related to the multiple time scales. These temporal scales are (1) information processing in the brain (milliseconds), (2) perception of events in the real outside world (seconds and minutes), (3) processing of these events, and (4) realistic behavior with cognitive tasks (hours and days). In

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[1] It is not necessary or even desirable to postulate conscious experience or awareness as a basis for active perception. To illustrate this point we've borrowed example from Freeman (2000; pp. 208): "…in the study of conditioned reflexes an observer does not need to know, and with animals cannot know, whether the subjects are aware of the stimulus, only whether a contingent response occurs in conjunction with patterns of neural activity in the brain that are accessible to observation."

general, the brain has to perform in a parallel manner many successive operations in order to achieve a successful result (Bak and Chialvo, 2001).

The fundamental concept of *operation* is common to an organizational structure of brain and mind. Both the material organization that characterizes brain and the informational order that characterizes mind therefore necessarily involve such events as operations at their cores. Here the *operation* is stand for the *process* or series of acts that are limited in time (Krippendorff, 2002). More generally operation is the state of being in effect. This provides a basis for discussion of the relative complexity of operations, where there is a more complex operation/operational act that subsumes the simpler ones (for a more detail conceptualization, see Fingelkurts and Fingelkurts, 2003). In this sense, a simplified description of the operation of a neuron is that it processes the electric currents which arrive on its dendrites and transmits the resulting electrical current to other connected neurons using its axon. Such "blind" neurophysiological operation, at the same time, is the elemental physical operation of the brain (Tabl. 1). Such operations have a fully neurophysiological ontology and they are completely NONconscious phenomena, which according to Searle (1992) have no mental/subjective ontology whatsoever. More complex physical operations of the brain emerge from the collective activity of many neurons – *neuronal assembly*[2]. It is well established, that single neurons (highly distributed along the cortex) can quickly become associated (or dis-associated) by synchronization of their activity and giving rise to functional transient assemblies (Kogan and Choraian, 1977; von der Malsburg, 1999). Anatomical connections are not necessarily important prerequisite for such synchronization; it is rather a stimulus (external – physical or internal – mental) and/or a task that is important and is the causal source of synchrony (see Ryder and Favorov, 2001). Each of these functional assemblies maintains discrete complex brain operations some of which may have already mental/subjective ontology in addition to their neurophysiological ontology (Tabl. 1): They process different attributes of object or environmental scene, thus being simple cognitive operations (Valera et al., 2001; Fingelkurts and Fingelkurts, 2003). The joint functionally connected activity of many neuronal assemblies produces already complex cognitive/mental operations[3] (Tabl. 1; see also McIntosh, 1999, 2000). Each neuronal assembly makes a specific contribution to the performance of complex cognitive operation, and the contribution is determined by the position which a particular neural assembly occupies within the richly connected, parallel, and distributed brain system (see Petersen and Fiez, 1993). The temporal synchronization of many operations of local neuronal assemblies together (*Operational Synchrony,* OS) gives rise to a new level of brain abstractness – metastable[4] brain states (for the review, see Fingelkurts and Fingelkurts, 2004). It is suggested that these metastable brain states or functional *Operational Modules* (OM), as we name them, underlie complex brain

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[2] A neuronal assembly may be defined as a group of neurons that cooperate to perform a specific computation (operation) required for a specific task (Nunez, 2000).

[3] Using the orchestra metaphor of Raichle (1999, p.44), it is so as "specific members of a large orchestra perform together in a precise fashion to produce a symphony, a group of localized brain areas performing elementary operations work together to exhibit an observable human behavior."

[4] The specific interpretation of metastability in the context of a specific theoretical model of the coordination dynamics of brain and behavior was developed by Kelso (1991, 1995). According to his theory metastability arises because of a specific symmetry breaking in the coordination dynamics. In our reinterpretation metastability arises in the brain because intrinsic differences in activity between the local neuronal assemblies are sufficiently large and they do their own job, while still retaining a tendency to be coordinated together in accordance with cognition and/or behavior (for the review, see Fingelkurts and Fingelkurts, 2001, 2003, 2004).

functions and/or mind complex operations (cognitive percepts and mental states that have representational nature)[5]. The sequence of these metastable OMs, thus, represents[6] the stream of thoughts (Fingelkurts and Fingelkurts, 2001). It is only at this level of integration we may hope relate brain and mind through *functional isomorphism* principle (see Fingelkurts and Fingelkurts, 2004).

Different parts of this very general picture of brain-mind functioning have been obtained from a large body of behavioral, cognitive, and physiological studies. For example, brain-behavior experiments (Fuchs et al. 1992; Fuchs et al. 2000; Kelso et al. 1992) have demonstrated that neural activity picked up by the magnetoencephalogram (MEG) and electroencephalogram (EEG) shows spatiotemporal transitions when the operation of behavior (movement pattern) switches. This research indicates that the ongoing brain activity is directly related to the behavioral coordination dynamics (Jirsa et al., 1998). The biological advantages of coordination transitions are obvious: They provide a mechanism for flexibility, allowing the system (brain) alternative ways to coordinate itself under changing environmental or task conditions. Thus, behavior implies dynamical sequence of patterns. Such view is in accord with the concept developed by Alexandrov (1999) and introduced by Anokhin (1973; 1978). According to this theory of functional systems, behavior is indeed a continuum of discrete behavioral acts performed by an individual during life. Any behavioral act consists of a number of appropriate operations (Shvyrkov, 1990). The following behavioral act in a sequence is realized only when the previous act is achieved and evaluated. The evaluation process is a necessary part of the organizational architecture of the following behavioral act and is usually rapid, thus, being transitional. During such transitive periods the redundant degrees of freedom of the whole system are eliminated and the decision of what should be done and how to achieve the adaptive result is made (Alexandrov, 1999).

Table 1. The hierarchy of brain-mind operations.

OPERATION	One neuron	One neuronal assembly	Several neuronal assemblies	Many Neuronal assemblies
Brain level	simple	complex	more complex	very complex
Cognitive level	—	simple	complex	very complex

From a daily phenomenological experience we are aware also of a discrete sequence of cognitive events, where conscious percepts, mental images and thoughts are constant within a snapshot of variable duration (Mangan, 1993a; Galin, 2000; Bickle et al, 2000). In science, the idea of discrete cognition and consciousness was firstly considered by William James

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[5] These states could be divided into two categories: unconscious mental phenomena and conscious mental phenomena (for a detail, see Searle, 1992).

[6] As has been stated by Antonio and Hanna Damasio (1999), such representations are not “pictorial” objects in the brain as was traditionally thought; instead they are the records of the neural activity that takes place in the brain during particular brain operation. Such records define perceived or imagined object and/or event. Generally each of these records can also activate related ones.

(1890). Stroud (1955) was the first who start to use the notion "*perceptual moment*". However, the notion of a "*time quantum*" was initially suggested by von Baer (1864) and important investigations in this vein have been further made by Geissler (1987; 1997). Later, Efron (1970) suggested that conscious cognition is temporally discontinuous and parsed into sensory sampling intervals or "*perceptual frames*." Based on behavioral studies it was shown that there exists a certain minimal interstimulus interval for which two successive events are consistently perceived as simultaneous: one can think of them as occurring within a single *discrete epoch* (Hirsh and Sherrick, 1961; Kristofferson, 1967; Andrews et al., 1996).

In recent years this vein of research has been extended to electrophysiology. Exactly cortical brain oscillations have been found to be closely related to temporal perceptual window (Varela et al., 1981; Gho & Varela, 1988). John (1990) proposed a mechanism, where a cascade of momentary perceptual frames converges on cortical areas to establish a steady-state perturbation (*spatiotemporal signature*) from baseline activity (John, 2002). This mechanism has received substantial support from EEG studies, including research by Lehmann and colleagues (Lehmann, 1971; Lehmann et al., 1987). They have demonstrated that the dynamic of the brain EEG field is represented by the intervals of quasistability or "*microstates*" and by *sudden transitions* between them (Strik and Lehmann, 1993; Pascual-Marqui et al., 1995). Furthermore, they have shown that these microstates have been associated with different modes of spontaneous thoughts (Koenig and Lehmann, 1996) and with spontaneous visual imagery or abstract thoughts (Lehmann et al., 1998).

Different Approaches to Study Brain-Mind Operation

Many theories in brain research try to capture the complex functioning of brain-mind. Amongst general approaches to study how the brain and mind function, there are currently three major types: the *dynamical* approach, the *symbolic* approach, and the neural information processing (*neurocomputational*) approach. While symbolic and dynamical approaches are quite disjoint, considerable overlap exists between each of these and the neurocomputational view (see Cariani, 2001).

Dynamical Approach

The dynamical approach for cognition and brain activity has been adopted in believing that systems of differential or difference equations are the most appropriate tool for modeling brain behavior (Van Gelder, 1995). According to this approach cognition is explained as a multidimensional space of all possible thoughts and behaviors that is traversed by a path of thinking followed by an agent under certain environmental and internal pressures, all of which are captured by sets of differential equations (Van Gelder and Port, 1995). For dynamicists, the brain is considered as a large and complex continuous-time physical system that is described in terms of the dynamics of neural excitation and inhibition (Freeman and Barrie, 1993). The behavior of large number of microscopic neural elements creates discrete basins of attraction for the system that can be switched (Haken, 1999; Tsuda, 2001). These contingently-stable dynamical macro-states form the substrates for mental and behavioral states (John, 2002). Thus, cognitive processes are not rule-governed sequences of discrete symbolic states, but continuous, evolving total states of dynamic systems determined by continuous, simultaneous and mutually determining states of the systems' components (Freeman, 2000). Representation in a dynamic system is essentially information-theoretic; though the bearers of information are not symbols, but state variables or parameters (Beer, 2000). There are several classes of models used within dynamical approach. One class is represented by the models of deterministic chaos (twist-flip maps and the Lorenz, Rössler, and Chua attractors). However, these models are low dimensional, stationary, autonomous, and essentially noise-free, so they inadequately model the brain, which fail to conform to any of these conditions (Freeman et al., 2001). The same is true for the attempts to measure correlation dimensions, Lyapunov exponents, and related numeric features of brain subsystems. These measures have failed to yield normative results and became less considered for brain modeling (Rapp, 1993). Another large class of models is represented by reaction-diffusion equations (chemical morphogenesis; Turing, 1952, and irreversible thermodynamics; Prigogine, 1980) that make "order from disorder". These models also fail, especially when they model the interactions within neural networks and populations (Freeman et al., 2001). Furthermore, it was shown that terminal chaos (Zak, 1993) is impaired in its utility for representing chaotic systems (Freeman et al., 1997). Models based on hydrodynamics and turbulence are unsatisfactory also; there is nothing equivalent to viscosity or to molar convection in neurodynamics (Freeman et al., 2001). The best available models are those from synergetics, which described microscopic particles as being "enslaved" by a macroscopic "order parameter" (Haken, 1991). Generally, dynamic system theories are not be able in any way to explain (1) discrete higher-order thoughts and images, (2) the qualitative or phenomenal character of experience, and (3) how cognitive systems can be both representational and computational (Eliasmith, 1996).

The Symbolic Approach

In the neural and cognitive sciences, the symbol-based approach has been adopted by research traditions whose subject matter lends itself to orderly, rule-governed successions of discrete functional states: The physical systems symbol hypothesis (Newell and Simon, 1976), language symbolic processing (Fodor, 1987; Fodor and Pylyshyn, 1988), symbolic artificial intelligence (Honavar, 1994). Symbol-based approach have proposed that the mind contains such mental representations as logical propositions, rules, concepts, images, and analogies, and that it uses mental operations such as deduction, search, matching, rotating, and retrieval. According to Fodor and Pylyshyn, in normal cognitive agents, there exist intrinsic connections between some thoughts and others. Thoughts (symbols) come in clumps. This putative fact is the *systematicity* of cognitive representations. The *compositionality* of representations says something about the nature of the thoughts that are intrinsically connected. It indicates the nature of the clumps of mental thoughts (symbols): The thoughts in the clumps are semantically related. For example, the thoughts in the clumps have common terms and predicates. Thus, the thoughts 'John loves Mary' and 'Mary loves John' are compositional sets of representations since they both represent 'John,' 'loving,' and 'Mary.' Perception here is seen in terms of microcomputations by discrete feature-detection elements, while mental operations are conceptualized in terms of computations on discrete, functional symbolic states that are thought to be largely autonomous of the underlying neural microdynamics. However, symbolic approaches (1) does a poor job of explaining graceful degradation of function, holistic representation of data, spontaneous generalization, appreciation of context, and many other features of human intelligence and cognition, (2) have ignored problems related to how new symbolic primitives can be created (Piatelli-Palmarini 1980; Schyns et al., 1998).

The Neurocomputational Approach

The neurocomputational approach includes a variety of neurophysiological and neurocomputational perspectives that seek to understand the neural coding – the identification of which aspects of neural activity convey information (Cariani, 1994; Mountcastle 1967; Perkell and Bullock 1968; Rieke et al. 1997; Uttal 1973; Arbib 1989; Churchland and Sejnowski 1992; Marr 1991; McCulloch 1965; Freeman et al., 2001). One of these perspectives is the connectionist model. It seems, that such models are particularly well matched to what we know about the brain. Indeed, the brain is a neural net, formed from massively many units (neurons) and their connections (synapses). Furthermore, several properties of neural network models suggest that connectionism may offer an especially faithful picture of the nature of mind. Neural networks exhibit robust flexibility in the face of the challenges posed by the real world. Noisy input or destruction of units causes graceful degradation of function. In such cases the net's response is still appropriate, though somewhat less accurate. In contrast, noise and loss of circuitry in classical computers typically result in catastrophic failure. Neural networks are also particularly well adapted for problems that require the resolution of many conflicting constraints in parallel. Despite these intriguing features, there are some weaknesses in connectionist models that bear mentioning. First, most neural network research abstracts away from many interesting and possibly important features of the brain and mind. Second, the claim that human brains and minds work by computation is an empirical conjecture and might be wrong. For example, Dreyfus (1992) and Searle (1992) have claimed that computational approach (1) neglects the important role of emotions, (2) ignores the importance of consciousness, (3) disregards the significant role of physical environments, and (4) neglects the fact that the mind is a dynamical system, not a computational one.

The debate between these three approaches is still intense and there is a fast growing literature built around the many issues raised by it. It is clear that neither approach described above is satisfactory in isolation; none of them exploit in an explicit way the actual physical/brain and subjective/mental operations the human brain-mind possesses in the course of organism behavior. The entire brain functioning is described in a somewhat one-side manner. There is, for example, no physiological explanation for abrupt changes in brain-mind states over time, and there is no means for deriving the time needed for brain-mind operations. When inevitable in such cases "paradoxes" appear, where human brain does not behave as the theory predicts, the standard response of the researchers is to alter the initial axioms of theories. This is apparently implausible and requires significant simplification. However, the operational organization of brain-mind functioning (as has been described in the Introduction section) may be an essential framework for cognitive neuroscience. Thus, there is a need for further explanatory theories to be introduced, which would be alternative and superior to either of described above.

Operational Architectonics Postulates

We have suggested the *Operational Architectonics* (OA) framework[7] (Fingelkurts and Fingelkurts, 2001; 2003) of brain-mind functioning, which is a metatheory and is a plausible illustration of the explanatory advantages of integrated view that adopts an approach which supposes from the outset that brain and mental processes essentially evolve over real time (a dynamical approach), have distinct microstates (a symbolic approach), which are the result of communication between neuronal assemblies (a computational approach). This framework explores the temporal structure of information flow and interarea interactions within the network of functional neuronal assemblies by examining topographic sharp transition processes in the scalp EEG (or MEG), on the millisecond scale. Thus, the OA theory may be a sufficient framework that accounts for data covered by three traditional approaches described above, but which explanatory capacities go beyond those of traditional theories in a number of respects. The OA framework, by contrast to other theories, sets out with the explicit aim to describe, measure and model the brain and mind operations involved in the complex human behavior which is governed by the individual's brain. According to the OA framework, the notion of operation[8] is central for perception, attention, intention, memory, action, and eventually consciousness (Fingelkurts and Fingelkurts, 2003).

In constructing OA, we have drawn on many ideas from other theoreticians especially, of course, those emphasizing the intimate relationship between brain and mind operations. For instance, we share the general perspective of Chalmers (1995) and Varela (Thompson and Varela, 2001) that brain/physics and mind/phenomenology are functionally linked and that it is only their coordination that allows for adaptive behavior. We further adopt the metastability notion put forward by Kelso (1991; 1995), Friston (1997; 2000), and Kaplan (1998), that is circumstantial for the interaction among the elementary neuronal systems in order to generate adaptive behavior within changing and not fully predictable environments. And we also follow Singer (1994; 2001) in assuming that representations of perceptual contents and action plans are content-specific composites of codes presumably stored in a distributed fashion, whereby synchronization of brain activities, going on in different brain areas, is a mechanism for the integration of local circuits within the large-scale anatomical structure and was claimed to be crucial for mental representations (Phillips and Singer, 1997). From a dynamical systems viewpoint, the best way to assess this large-scale level of synchronization is through EEG and/or MEG measures (Nunez, 2000; John, 2002; Freeman, 2003; Basar, 2004). The main three principles utilized by OA concept are (1) the neuronal assembly notion suggested by Hebb (1949) and developed by von der Malsburg (Malsburg, 1999; Triesch and von der Malsburg, 2001), (2) the large-scale description of information processing in the

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[7] This framework takes its direct origin and is rooted in the work of Kaplan and colleagues (Kaplan, 1995, 1998; Kaplan et al., 1997; Kaplan & Shishkin, 2000; Kaplan et al., 2001).

[8] There is, admittedly, a strong, fallible, assumption that the system is divided into components performing different elementary operations (Bechtel, 2002). Petersen and Fiez (1993), for example, stress that neuroimaging should be seeking to identify elementary operations, not tasks.

brain (Nunez, 2000; John, 2002; Freeman, 2003; Basar, 2004), (3) the importance of human consciousness; the work by Chalmers (1995; 2002), Baars (1988; 1997), Edelman and Tononi (2000), Crick and Koch (2003), and Revonsuo (2000; 2001). Below we will discuss each of these principles in detail.

Transient Neural Assemblies

It is now well appreciated that integration of distributed brain activity involve the activities of large number of neurons (deCharms and Zador, 2000). However, there are basically two ways how to describe the mass behavior of neurons (see Hatsopoulos et al., 1998; deCharms, 1998): (1) as by pooling together large number of essentially *independent* neuronal signals (The Independent-Coding Hypothesis), or (2) through the essential *coordination* of neuronal elements into a single signal, as in a symphony (The Coordinated-Coding Hypothesis). According to the independent coding framework each cortical neuron represents a separate signal. Although many neurons may be involved in coding a particular object, the key postulate of the independent-coding hypothesis is that all of the information that can be obtained from any one neuron can be derived from that individual neuron alone, without reference to the activities of others (Georgopoulos, 1990; Schwartz, 1994a,b). It has been proposed that such independent signals may be overlapping, noisy, or redundant and may need to be pooled or averaged over large populations to become clear, but the signal carried by each neuron is carried independently (see deCharms and Zador, 2000).

The coordinated-coding hypothesis, on the contrary, suggests that the dynamic patterns of cooperative activity of neurons cannot be predicted from knowledge of the activity patterns of any single class of neurons, or individual neurons (Mountcastle, 1998). According to this hypothesis the coordinated information could be extracted from the relations between multiple neurons in a population, whereby these relations are reflected in the neural synchrony (Gray et al., 1989; Singer and Gray, 1995). Indeed, it has been shown that changes in such synchrony (a) are stimulus frequency specific, (b) follow the time course of ongoing stimuli, and (c) are systematically mapped across the cortical surface (deCharms and Merzenich, 1996). Here the emphasis is put on the functional brain units or assemblies (von der Malsburg, 1999) executing the basic elemental operations of informational processing (Finger, 1994; McIntosh, 1999; Varela et al., 2001; Crick and Koch, 2003).

Before moving further, we need to be clear about how elementary the operations in question might be (Bechtel, 2002). In a broad sense, basic physics defines elementary operations of all phenomena in nature in terms of quantum mechanics. However, this is typically not necessarily the right level at which we are searching the basic operations that comprise the explanation of a cognitive phenomenon. To illustrate this point we have borrowed example from the Bechtel (2002; p. 233): “To explain how a car generates locomotion we do not jump immediately to quantum mechanics. Rather, we appeal to parts at one level of decomposition down from the whole car – the engine, drive shaft, axles, etc. Each of them makes a contribution which we can understand in light of the goal of generating locomotion – transforming chemical energy to mechanical energy, etc.” Similarly, if we are interested in a quest to find the brain operations that comprise the elemental cognitive operations, we should define the appropriate level of brain description.

The individual neurons are seen as imperfect and unreliable pulse generators, partly due to thermal fluctuations in the membranes of their trigger zones, and partly due to their biochemical nature (Freeman, 2000). Moreover, most of the activity of single neurons is expected to be determined by the activity of their peers and only the small part of such activity is determined by the features of the environment (Buzaki, 2004). It has been also stated that individual neuronal activity is only weakly correlated with cognition and behavior. Indeed, the response properties of individual neurons tend to vary only little in awake, sleeping, and anesthetized brains, meaning that the tuned responses of individual neurons are alone not sufficient to support cognition and consciousness in particular (Singer, 2001). Revonsuo in his analytic paper also comes to the same conclusion: "…it appears that the records of single-cell firing rates are not explanatorily adequate for the discovery of the phenomenal level, for we have no idea how the firing rate of a neuron is supposed to contribute to the subject's phenomenology and, consequently, we have no clue how to reconstruct any aspect of the subject's phenomenology from the firing rate data alone." (Revonsuo, 2001; p. 12). When we record activity from the single cells, we observe brain activity at a very low level of organization – we trace the elemental brain *physical* operations – and such observations never allow the visualization of the phenomenon (cognition or mind) we are interested in (for a detail discussion, see Revonsuo, 2001). Thus, the level of the activity of individual neurons (elemental brain physical operations) is most likely an inappropriate level of brain organization for realization of cognition and mind. However, there must be some level of organization in the brain that literally resembles or is *isomorphic* to cognition, that is to say cognition (or mind) itself. So, the appropriate level of brain description should in some way allow reconstruction of the structure (or at least some aspects of it) and/or content of phenomenal level of organization experienced by the subject.

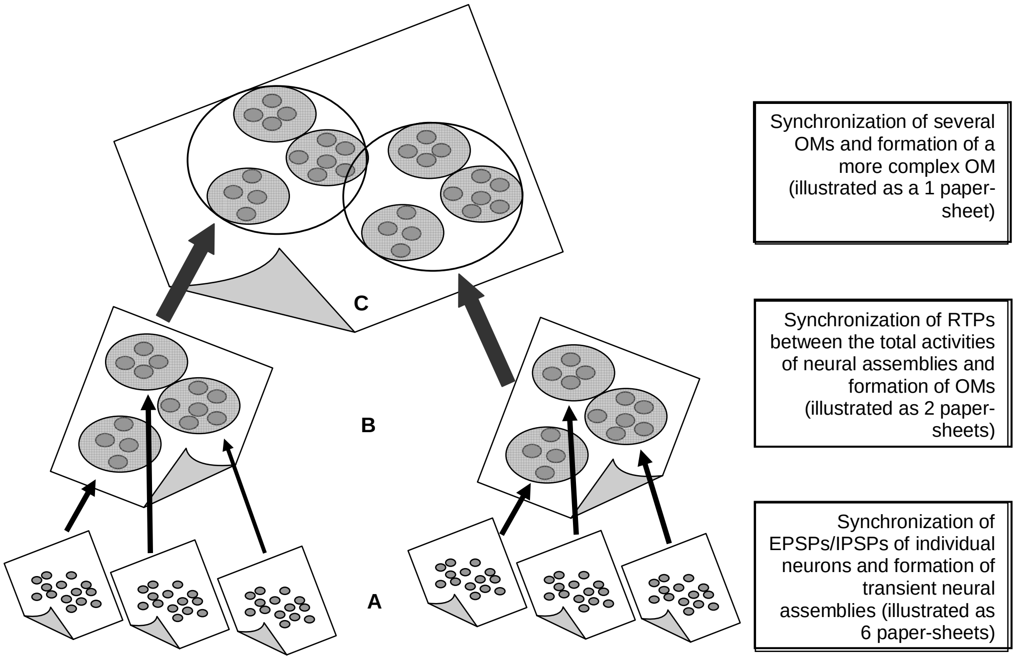

Figure 1. Schematic illustration of operational architectonics of brain functioning. *A*, Microscopic level of individual neurons. *B*, Mesoscopic level of transient neuronal assemblies. *C*, Macroscopic level of operational modules (OMs). *EPSP/IPSP*, excitatory/inhibitory postsynaptic potential. *RTP*, rapid transition periods in electromagnetic field. Figure is modified from Fingelkurts et al., 2005, Progress in Neuropsychopharmacology & Biological Psychiatry ©.

The elemental cognitive brain operations (perception, object feature representation, recognition, and so on) appear to require some kind of "devices" that bridge distances and allow for the fast between-neuron exchange of information. In another words, information represented in some class of neurons has to be bound[9] (Fig. 1 A). Neuronal assemblies are perfectly suited to fit this purpose[10]. Nowadays, in the result of the paradigm change, it seems clear that the coordinated-coding framework, or a theory of neural assemblies plays more and more central role in cognitive sciences (Basar, 2004). Here, the activity of any individual neuron is informational only insofar as it contributes to the overall statistics of the assembly of which it is a member (John, 2002). For example, hippocampal pyramidal cells during rest and sleep produce strongly coherent ensemble bursts believed to be critical in transferring information to the neocortex. Although robust at the assembly level, no amount of sequential single-cell recording could reveal such cooperative patterns (Buzsaki et al., 1992). Thus, it has been claimed that the cell assembly theory (which describes the *intermediate-level organization* of the brain) seems the only plausible concept that bridges the gap between neural and mental dynamics[11] (Palm, 1990; Eichenbaum, 1993; Pulvermueller et al., 1994; Mountcastle, 1998; von der Malsburg, 1999; Varela et al., 2001; Basar, 2004). According to this theory, higher brain functions (cognition) are based on processing units called cell assemblies (Pulvermueller et al., 1994; Crick and Koch, 2003). Such neuronal assemblies, thus, is thought to serve as the functional elements of brain mental activity – elemental *cognitive* operations[12] (Fingelkurts and Fingelkurts, 2003; see also Basar, 2004). If cell

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[9] The communication of neurons within the assembly is achieved through the synchronous operations executed by each neuron. Such synchronization occurs among the neurons which tune preferentially to a particular features of their sensory environments and are predictably related to other such features (Phillips and Singer, 1997). It is supposed that this process relay on self-organization (Erdi and Barna, 1984; Singer, 2001) where the crucial role is played by dendrites (Ryder and Favorov, 2001).

[10] Neuronal assemblies allow also overcoming the unavoidable unreliability of individual neurons (see above). By having numerous elements in parallel, a consensus can be found by averaging among them in order to extract a clean signal – this solution is very well known by engineers (Freeman, 2000).

[11] Only observing statistically representative groups of the neurons can reveal such emergent phenomena as cognition.

[12] This view is alternative to both localizationist and holistic approaches (Pulvermueller, 1999). Localizationists would assume that small cortical areas are fully capable of performing complex cognitive operations. A localizationist would, for instance, propose that a small brain area is the locus of word comprehension (Broca 1861; Lichtheim 1885; Wernicke 1874). According to this view, each complex cognitive operation is restricted to one area – that is, no other areas are assumed to contribute to this specific process. In contrast, a holistic approach would imply that the entire cortex exhibits equipotentiality with regard to all cognitive operations and that all cortical areas can contribute to sufficiently complex mental processes (for discussion see an overview, Deacon 1989). The neuronal assembly theory is in sharp contrast to both of these views (Pulvermueller, 1999). Cell assemblies with defined cortical topographies are assumed to form the neurobiological representations of elemental cognitive operations, whereby complex cognitive operations are represented by the joint activity of many neuronal assemblies at another time scale (Fingelkurts and Fingelkurts, 2003). To illustrate this, lets consider the following example: The elemental cognitive operation lasts some short period *T*. Then at times shorter than *T* one should speak about cognitive (or brain) microstate, whereas at times greater than *T* one observes a succession of microstates (or a state history). The combination

assemblies are the basic units of cognition, they must become active when cognitive processes take place. It is known from animal experiments that synchrony (is taken as an indicator of reverberating activity in cell assemblies, see Merzenich and deCharms, 1996) of neuronal activity reflects gestalt criteria, for example the fact that two objects move together (Singer 1995; Singer and Gray 1995). Further support for the role of neuronal assemblies in cognitive processing comes from studies of electrocortical responses to different memory stages (Fingelkurts et al., 2003a). Moreover, gestalt-like figures such as Kanizsa's triangle have led to stronger EEG responses when compared to physically similar stimuli that are not perceived as a coherent gestalt (Tallon et al., 1995; Tallon-Baudry et al., 1996). It is well documented that the simplest inputs such as single words lead to activation of broad patterns in brain scans. There is no way to accept that the input of a single word would activate such a large fraction of the neurons unless the group activation process is the normal response of the brain (Epstein, 1999). Even more, there is known fact that seeing only the first few letters of a word can create a whole word in our minds; it also shows that a neuronal assembly can be normally activated by those first inputs (Epstein, 1999). It has been even suggested that if cognitive processing does not take place, neuronal assemblies do not become active[13] (Pulvermueller et al., 1994).

Hebbian Neuronal Assemblies

Early attempts to build the neuronal assembly theory can be traced back to Donald Hebb, who in 1949 proposed that the coactivation of connected cells would result in a modification of weights so that when the presynaptic cell fires, the probability of the postsynaptic cell firing is increased[14] (Hebb, 1949). This implying that group of neurons that have the tendency to fire together will become strengthened as an assembly. Such principle is known as "the principle of cooperativity". Another principle was suggested later – it is "the correlation learning": Connection strength is not only modified by coincident activity, it also changes if only one of two connected neurons is active while the other one is inactive (Pulvermueller, 1999). These two principles have to have two important functional consequences: (1) If a sufficiently large number of the assembly neurons are stimulated by the input (either through sensory input or by internal image), activity will spread to additional assembly members and, finally, the entire assembly will be active. This explosion-like process has been called ignition of the assembly (Braitenberg 1978). (2) After an assembly has ignited, activity will not stop immediately (because of fatigue or regulation processes), but the strong connections within the assembly will allow activity for some time (Pulvermueller, 1999). Hebb's postulates have been extended into various forms of correlation-based rules and intensively used in many

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of local microstates together will form cognitive (or brain) macrostate that will last some time *Ti* and will have its own history at times greater than *Ti*.

[13] More precisely, cell assemblies may be stimulated and, therefore, become slightly active, but no full activation, no ignition, should take place.

[14] This view corresponds with one of the basic ideas of the Russian neurophysiological school: In the first third of previous century Vvedensky (1906) and Ukhtomsky (1935) proposed that connections between nervous structures are promoted through the correspondence in their frequency characteristics, that is, in equalizing their excitation cycle rate. This is known as the "functional lability" parameter (Ivanitsky and Nikolaev, 1999).

learning networks and in the analysis of activity-driven refinement of developing circuits[15] (Sejnowski and Tesauro, 1989; Brown et al., 1990; see also review by Bi and Poo, 2001).

Even though the explanatory power of neuronal assembly theory is very high and it is the right level of brain organization for the cognition, there is a major problem with using Hebbian cell assemblies to explain perceptual and cognitive processes. For one thing, they are too slow and rely on learning by repetition at a low-level (single neurons) organization of the brain. However, a great part of our cognition and perceptions are fast, unique, and singular in a veritable sense (Bauer and Dicke, 1997). For example, we can perceive individual objects that we see only once, and never again, within a fraction of a second. The coherency of perceptual and cognitive states is achieved rapidly and effortlessly (Edelman and Tononi, 2000). It is obvious that neuronal representations of such objects and related cognitive processes cannot be based on slow anatomical cell assemblies (Bauer and Dicke, 1997). Instead, *functional transient neuronal assemblies* may be appropriate for the purpose since they are fast and do not necessarily depend on the anatomical connections[16] (von der Malsburg, 1999; see also Fingelkurts et al., 2005a).

The other general problem with Hebbian neuronal assemblies is that they have no flexible means of constructing higher-level operations by combining more elementary operations (Fodor and Pylyshin, 1988). It is known as “the binding problem” (von der Malsburg, 1981). To illustrate this, lets consider the following classical example: Imagine that two objects need to be activated/represented in the same mental state in order to be compared. Such coactivation would inevitably lead to what has been named “superposition catastrophe”, whereby two neuronal assemblies according to the classical concept will merge into one, and there will be no possibility to express the information needed to subdivide the composite state into its components (von der Malsburg, 1999). So far, the only reliable solution lies in the fast transient neuronal assemblies which (being the discrete functional units[17]) are capable of combinatorial mechanisms through the temporal synchrony of their total activities (Fig. 1 B). As a result they may form the complex units which have explicit structure on the basis of which elements of this structure can be compared, recognized, decomposed, and further combined to build new or even more complex structures (Fig. 1 C; see also Fingelkurts and Fingelkurts, 2003). This is the neural architecture that has the capacity for flexible learning and self-organization (for the review, see Fingelkurts and Fingelkurts, 2004).

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[15] An exciting application of modified Hebbian rules is in a new type of neural network models – the “pulsed neural networks” (Maass and Bishop, 1999) that use precise timing of individual spikes to encode information. Such temporal coding may enable construction of more versatile and powerful networks because it provides larger coding capacity and easier handling of temporal information (Bi and Poo, 2001).

[16] The assembly of neurons which are connected by functional connectivity has been also called “dynamical cell assembly” (Fujii et al., 1996). The important point to note is that neurons composing a dynamical neural assembly need not be fixed; that is to say, a set of neurons joining the assembly may alter in time (Watanabe et al., 2001).

[17] Cell-assembly size is currently estimated to lie between several hundred and about a million neurons (Palm, 1982; 1993). It is relevant to point out here that the boundary between neuronal assemblies is necessary fuzzy. And it is not a problem, since there will be some neurons with high correlations and others whose correlation with these “core neurons” are smaller (Pulvermueller, 1999). In other words, some neurons will always become active together when a certain input pattern is provided, others may only be recruited in some cases, depending, for example, on the neuronal sets activated in the past (Milner, 1957).

Transient Functional Neuronal Assemblies

Katchalsky (1974) was the first who start to study the self-organized behavior of fast cell assemblies. The distributed interactions among neurons that arise in neuronal cell assemblies "enslave" the mass of cortical neurons (Haken, 1999). More precisely, with convergence, each receiving neuron sums the dendritic currents triggered by neurons broadly scattered over the transmitting cortex[18] (Freeman, 1992). The only activity that survives this spatial integration is that which has the same instantaneous frequency and phase over the spatial extent of the integration[19], whereas the stimulus-locked activity that is not spatially coherent is washed away (Freeman, 2000). The activity that has this property is the common carrier wave generated by the cortical interaction, which conveys the amplitude modulation patterns. The consequence is that the raw sense data, which can be regarded as a representation of each particular stimulus, is "deleted" by the brain as noise, and the self-organized amplitude modulation pattern is accepted as the signal, that is, the meaning for the individual of the class of the particular stimulus (Freeman, 2000). By tuning or choosing delays and connection weights, functional neural assemblies can be constructed that are differentially sensitive to particular time patterns in their inputs. Assemblies can also be formed that emit particular temporal patterns when activated (John and Schwartz, 1978). Thus, the most significant property of such functional ensembles is the capacity for undergoing rapid and repeated global state changes (Freeman, 2000a,b). Formation of new neural assemblies is then a means by which the brain can adaptively construct what are in effect new measuring "devices" that make new distinctions on an internal milieu that is richly coupled to the external world (Cariani, 2001).

The activity of these neuronal assemblies represents the mesoscopic level of brain organization (the term has been introduced by Freeman in 1992; see also Freeman, 2000c; Freeman et al., 2001). Mesoscopic effects operating at spatial and temporal scales of 1 cm and 100 ms mediate between the two extremes of single neurons and the major lobes of the forebrain. They correspond in size to Brodmann's areas and in duration to psychophysical events that compose perceptions. Thus, mesoscopic effects provide a link between extreme local fragmentation and global uniformity (Fig. 1 B). They change continually in space and time, requiring a very close relationship between dynamic events, e.g. amplitude modulation of local field potentials, and the media through which the propagation occurs (Freeman, 1992; Skarda and Freeman, 1987).

There is intensive research of inherent relation between local field potentials produced by neuronal assemblies[20] and cognitive operations. Thus, it has been demonstrated that local field potentials change in motor (Vaadia et al., 1995; Donoghue et al., 1998; Lee, 2003) and sensory (de Oliveira et al., 1997; Super et al., 2003) cortices during periods in which the

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[18] This is how brains do spatial ensemble averaging. There is no need to store the traces of activity.

[19] It is a set of emergent properties of abundant amounts of elements in assembly that is important. In this sense, the representation of information by neuronal assemblies is ergodic; the same as the generation of pressure by water molecules in an enclosed volume (John, 2001). Because of this, the representation of information by neuronal assemblies is also robust, meaning that damage to a single cell (or cell mortality) will not have a catastrophic effect on the representation of information. Additionally, neuronal assemblies have other key important properties, such as mechanism for noise removal, short-term memory and the instantiation of complex, nonlinear functions (Pouget et al., 2000).

[20] Oscillations in the local field potentials are normally taken as evidence of coherent oscillations among the group of neurons contributing to the field potential (Averbeck and Lee, 2004).

animal is anticipating behaviorally relevant events. Similarly, group of neurons in motor cortical areas display coherent oscillations during demanding tasks, or task epochs presumably requiring cognitive effort (Murthy and Fetz, 1996). Other studies have shown that synchrony (Steinmetz et al., 2000) and oscillations in the local field potentials (Fries et al., 2001) can be modulated by attention to a particular location in the visual field or to a particular sensory modality. These experiments suggest that coherent oscillations might be involved in the realization of cognitive operations, because they appear when the subject is preparing to process specific sensory stimuli, or is selectively processing a subset of the available sensory stimuli. Some of the more compelling data in support of this idea come from analyses of error trials. Three studies have shown that, when subjects do not execute correct responses, coherent oscillations are reduced (Woelbern et al. 2002; Lee, 2003; Super et al., 2003), suggesting that the absence of coherent oscillations reflects a failure in the flow of information. Generally speaking, "the transitions between walking and running, speaking and swallowing, sleeping and waking, fast changes of objects and scenes in the visual field and at last the staccato flow of thoughts and mental images are all realized by transient functional neuronal assemblies" (Freeman et al., 2001).

In conclusion, we should stress that functional neural cell assemblies, though powerful by themselves, are also ideal building blocks for larger cognitive structures or complex cognitive operations (see Fingelkurts and Fingelkurts, 2001; 2003; see also Kaplan et al. 1990; Holland 1998).

Operational Synchrony and Operational Modules

The recombination of subsets of activity of neuronal assemblies (elemental operations as functional building blocks) into larger spatial-temporal structures yields a vast number of potential combinations (Fig. 1 C; see also Fingelkurts and Fingelkurts, 2004), thus providing the base for a practically infinite number of mental states and thoughts of different complexity (Fingelkurts and Fingelkurts, 2003). Just as functional connectivity (or *Operational Synchrony*, Fingelkurts and Fingelkurts, 2001) forms transient neuronal assemblies, the same principal of functional connectivity can be used to create an associative links between two or more of such assemblies[21] (Fingelkurts et al., 2005a). Neurophysiologically, each local pattern that appears as a result of neuronal assembly activity depends on its interactions with the others to which it is functionally connected (Mumford, 1994). Because the interactions between cell assemblies are inevitably mutual, the situation is not that of one assembly imposing its pattern on another, but rather of multiple assemblies acting to constrain the pattern in each other (Bressler, 1999). Pattern constraint is a potentially powerful mechanism

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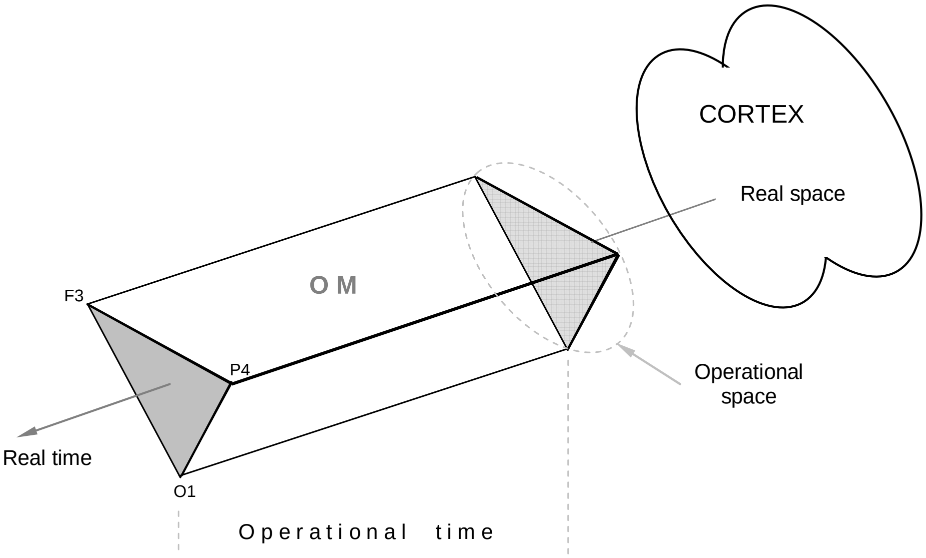
[21] This is possible just because the mesoscopic patterns of brain activity produced by different neural assemblies all have the same "format" (Freeman, 2000c). This indicates that the several such patterns (which represent elemental cognitive operations) can be as easily integrated with each other, leading to the formation of a more complex spatial-temporal pattern – the operational module (OM) that represents complex cognitive operation (Fingelkurts and Fingelkurts, 2001). Thus, functionally, the outcome of coincident operations is an OM rather than larger ensemble of particular neurons firing in synchrony (Cariani, 1997). Here the time dimension is very important – time structure is the organizing currency of the brain-mind system. Time structure is preserved within OM in a sparse and distributed form. Information processing in such OM would be statistically-mechanical in nature, implementing temporal binding of simpler operations on the all-order interval statistics of a larger operation and consequently a larger OM (Fingelkurts and Fingelkurts, 2003).

for the formation of novel complex dynamic coordination patterns in large-scale networks. Indeed, different brain operations executed by spatially distant neuronal assembles tend to be synchronized if they happens to be at the same time, thus related to the same perceptual/cognitive act (Cleeremans, 2002). Hence, the resultant spatial-temporal pattern or *Operational Module* (OM) is the emergent product of the synchronized simple operations of a set of strongly associated neuronal assemblies (Fig. 1 C); and these OMs represent the realization of cognitive complex macrooperations[22]. Here the notion of *operational space-time* should be introduced. It is not easy to grasp exactly what we need to explain, however, such notion is important for our conceptualization. Intuitively, the operational space-time (OST) is the abstract space and time which is "constructed" by the brain each time when the particular metastable OM emerges. Formally, the OST means that for a particular complex operation, the spatial distribution of the neuronal assemblies' locations with synchronous activity at repetitive instants of time (beginnings and ends of simple operations) builds the OM. These distributed locations of neuronal assemblies are discrete and their proximity or the activity in the in-between area, delimited by the known locations, is not considered in the definition (only the exact locations are relevant). Also, between the moments in time that particular locations of the neuronal assemblies synchronize, there can be smaller subset(s) of these locations synchronized between themselves or with other neural locations, though these do not relate to the same space-time of the same OM. The sketch of this general idea is presented in figure 2.



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[22] Similar view may be found in Bressler (1999; 2002): Local neuronal assemblies are considered to serve as associative memories for specific elementary types of information. But each local associative memory is coupled with a number of others according to the topological ordering of functional connectivity. Thus, cognitive structure depends not only on local stores of information, but also on heightened probabilities of conjunction among domains of knowledge stored in separate cortical areas. Context for processing in each neuronal assembly, hence, is provided by constraints imposed by the states of the other assemblies with which it interacts. Of course, not every OM constitutes a mental state or thought. Moreover, even in those, which do, the large amount of purely physical brain processes contribute to the construction of OM. However, from the level of OM there is no access to the original raw data anymore (Fingelkurts and Fingelkurts, 2003).

Figure 2. Operational module (OM) and operational space-time (OST). Each OM exists in the OST, which is "blind" to other possible time and space scales present simultaneously in the brain system. In the other words, all neural assemblies that do not contribute to a particular OM are temporarily and spatially excluded from the OST. F_3, is the left frontal area; P_4, is the right parietal area; and O_1, is the left occipital area. As an example, only neural assemblies in these areas (operational space) synchronize their operations on a particular (operational) time-scale.

The communication of activity from microscopic single neurons to feature-specific neural assemblies and yet to the large-scale distributed networks, been a pressing neurocognitive problem, may be elucidated through the present framework. This framework is in agreement with the Breakspear and Stam (2005) conceptualization of the brain as a constrained multiscale system in which emergent dynamics at any scale have a critical influence on the activity in larger and smaller scale structures. Thus, the "transition" of the same neural assembly into the new OM, in accordance with participation in the realization of another complex cognitive operation, must depend on the ability of this neural assembly to adapt to the main variables of the new OM. Thus, discrete parts of the neural networks (or assemblies) may gain another functional meaning when they are recruited by other OM and, therefore take part in realization of another perceptual or cognitive act (Fingelkurts, 1998; Fingelkurts and Fingelkurts, 2001; Fingelkurts et al., 2003a,b). In this process, some local networks (assemblies) in the large-scale network become temporarily coordinated (formation of OM), while others are temporarily excluded from participation in the coordination state. Furthermore, the spatial activity pattern within each coordinated local neural assembly, representing its contribution to the large-scale pattern (indexed as OM), becomes temporarily stabilized, thus implementing the metastability principle (Kelso, 1995; Kaplan, 1998; for the recent review, see Fingelkurts and Fingelkurts, 2004).

The importance of such large-scale operational synchrony for the cognition and mind was shown experimentally. For example, it has been demonstrated that functionally distinct cortical regions might be preferentially operationally synchronized and involved in different stages of memory processing such as encoding, retrieval, and retention (for details, see Kaplan and Shishkin 2000; Fingelkurts et al., 2003a). This was expressed through a gradual increase in operational synchrony process together with a growth of cognitive loading[23] (Kaplan et al., 1997; Fingelkurts et al., 2003a). Thus, the principle finding was the existence of systematic specific functional combinations among cortical areas (OMs), which changed significantly along with the memory stages shift (Fingelkurts et al., 2003a). These findings are also in agreement with the works of McIntosh (1999), Fuster (1997), and Basar et al. (2001). In another study, using a robust illusion known as the McGurk effect (McGurk and MacDonald, 1976), it was demonstrated that the apparent synthesis of information from different modalities might be achieved through the process of operational synchrony between modality-specific and non-specific cortical areas (for a detail discussion, see Fingelkurts et al., 2003b). The temporal synchronization of cortical operations processing unimodal stimuli at different cortical sites reveals the importance of temporal features of auditory and visual stimuli for audio-visual speech integration. The main principle lies in the systematic moment-by-moment synchronization of the operations produced by different neural assemblies (Fig. 1)

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[23] In contrast, subjects who failed to memorize the task, showed the negative process of operational synchrony, meaning that the particular brain areas actively unsynchronized their operations (Fingelkurts, 1998).

within the large-scale networks (Kaplan and Shishkin 2000; Bressler and Kelso, 2001). Thus, the well-timed spatiotemporal synchronization patterns (indexed by OMs) related to audio-visual integration were obtained. The subjects, who did not display the McGurk illusion (meaning that they lacked conscious multi-sensory integration), in contrast, demonstrated significant uncoupling[24] (negative values of operational synchrony) of particular brain areas (Fingelkurts et al., 2003b). These findings are in keeping with recent studies (for review, see Calvert, 2001), suggesting that multisensory integration is a process that not only facilitates detection of the multisensory stimuli by amplification of the unimodal sensory signals, but also combines these signals to form new and emergent multimodal representational percepts (O'Hare, 1991). Currently, it has been demonstrated that psychotropic drugs (in particular benzodiazepines) may significantly modify OMs and alter metastability of brain activity in healthy subjects. (Fingelkurts et al., 2004a,b).

Generally, OM has a more complex structure than operations which constitute it. OM is a gross abstraction of the brain state (Fig. 1 and Fig. 2), where much of brain state information is not transparent for the level of subjective phenomenology[25] (for detail conceptualization see Fingelkurts and Fingelkurts, 2003; see also Arbib, 2001). Such interpretation was already established by early philosopher Thomas Aquinas (reprint, 1952) who concluded that single events in the material world are not knowable, and that knowledge comes only through abstraction and generalization from the "phantasmata" of raw sensory impacts.

Properties of Operational Modules

OMs have several unique properties important for cognitive and mental activity of the brain. First is the property of *associativity*, by which the activation of a particular pattern in one local assembly co-activates linked patterns in other local assemblies (Rauschecker, 1995). This capacity is essential for joining together related information from different knowledge (or sensory) domains, such as in the association of names and visual images or auditory and visual information. However, this association is not merely a conditioning of one pattern by another, since it occurs within the overall framework of cognitive structures (Deese, 1970). The co-activation of patterns in different cortical areas is constrained by the patterns of connectivity formed between those areas. In short, association always occurs within the context of cognitive structure (Bressler, 2002).

Second important property of OMs is *dispositionality*, a characteristic of cortical function that has been extensively discussed by Damasio (1994). What this means in the present context is that the activity patterns of some local assemblies serve a dispositional role in directing the coordination of other local assemblies. Local dispositional networks interact in the same way as local sensory or motor networks (Bressler, 2002), but the information they provide serves to specify the composition of the large-scale coordination pattern – OM in our

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[24] Note, that the suppression of interactions between cortical areas was achieved not by inhibition responses, but rather by a sufficient degree of temporal dis-coordination of operations (see Fingelkurts et al., 2004a,b).

[25] Our OMs resembles Damasio's (2000) second-order neural patterns in several respects: It is an representation of perceived (or imagined) object (or scene) which is formed through an unfolding succession of signals related to this object/scene; it arises transiently out of interactions among a selected several neuronal assemblies; several such patterns can form composite and integrated pattern which would give rise to a new experience (we may call them the third-order neural patterns).

interpretation. The recruitment of a dispositional neural assembly into an OM can thus serve to recruit additional sets of specific local assemblies. Each recruited set may contain other dispositional networks with the potential for recruiting even further sets. In this way the cortex may evolve through a series of large-scale coordination states. Thus, dispositional networks may significantly contribute to the ability of the cortex to manifest a temporal progression of logically connected mental/cognitive states (Bressler, 2002). Dispositional networks in the cortex may exist at different hierarchical levels above the primary sensory and motor areas, and different areas may potentially contribute to the orderly evolution of the cognitive states.

Another advantageous property of OM is the *intermittency*. It is the degree of coordination of the component parts over time, when this degree can abruptly increase (Bressler, 2002). Indeed, distributed sets of cortical areas may remain uncoordinated for some time, and then, with a change in cognitive state, suddenly become coordinated through a rapid increase in operational synchrony (Fingelkurts et al., 2003a,b).

The last and the most important property of OMs is their *metastability* (Kelso, 1991, 1995; Kaplan, 1998; for the resent review see Fingelkurts and Fingelkurts, 2004). Metastability may allow the cortex to enter into many different states of coordination of its constituent areas without becoming trapped in any one state (Bressler, 2002). More precisely, in a metastable regime of brain dynamics, the interdependence of separate areas is balanced between integrating and segregating activities (Kelso, 1991, 1995; Friston, 1997; Kaplan, 1998). This property provides the cortical system with the flexibility necessary to rapidly adapt at both large-scale and local levels to changing contingencies required for a cognitive function. This flexibility may be advantageous for cognition if it allows the cortex to carry out a variety of tasks simply by changing the coordination states of its networks (Bressler and Kelso, 2001). Thus, different kinds of spatial-temporal patterns (OMs) can be present/sent over the same transmission lines at different times or even interleaved together without being functionally confused (Fingelkurts and Fingelkurts, 2003).

This raises the possibility that the structure of functional organization of informational process in the brain is *isomorphic* to the operational structure of the cognition, and on a more abstract level, to the phenomenological structure of awareness and consciousness (Fingelkurts and Fingelkurts, 2001). Indeed, one can see that the structure of electrical brain field, structure of cognition and the phenomenal structure of consciousness have the same construction: the succession of discrete and relatively stable periods (OMs, cognitive acts or thoughts) separated by rapid transitive processes (abrupt changes of OMs, cognitive acts or thoughts)[26]. In this interpretation, ordered sequences of OMs generated from within the brain system would have the character of successions of mental symbols, and reformulating Bressler (2002) these would be experienced as thoughts. This phenomenon is usually referred as a “stream of thoughts”[27] (James, 1890; for resent developments see Mangan, 1993a,b; Chafe, 1994; Galin, 1994, 2000). Further, the OM’s patterns that are related to goal-states would then have the character of system imperatives to adjust behavior, and thus would be experienced as desires and pains; and actions would be experienced through their effects on perceptions, sensory, and hedonic states (Bressler, 2002).

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[26] For similar ideas see also O'Brien and Opie, 1999a,b.

[27] According to this metaphor, consciousness is always changing, but it presents us with a series of substantive thoughts that are themselves momentarily stable and unified (James, 1890).

In the framework of operational architectonics (OA) framework, OMs (being by themselves the result of synchronized operations going on in different brain structures) could be also operationally synchronized[28] between each other (on the new time scale), thus forming more abstract and more complex OM that constitutes new integrated subjective experience (Fingelkurts and Fingelkurts, 2003; this idea coheres with O'Brien and Opie, 1999b). When two or more active OMs are cross-correlated and synchronized through continuous operational synchrony, a further complex OM[29] arises that maps these two (or more) independent simple OMs to each other within the operational time, which in its own turn is mapped onto real time. Different properties of the perceived scene thus can be integrated in order to form an operational whole, which now has higher level of abstractness[30]. The opposite process is also possible when complex OM could be decomposed to simpler OMs, whereas each of which would give rise to a distant subjective experience. However, the price for this decomposition is narrowly *focused attention* and consequently the *focused mental (conscious) state* (von der Malsburg, 1997). Thus, attention could be the possible mechanism that guides decomposition or construction of OMs of different complexity[31] (for detail conceptualization, see Fingelkurts and Fingelkurts, 2003).

Practical Implementation

In the light of our discussion, what is the appropriate method for functional brain imaging, considering that this method should have the capability of revealing the mesoscopic level of brain organization, which is directly involved (as it has been discussed earlier) in the realization of cognition and, eventually, consciousness? As it was already mentioned above, the time-scale of mesoscopic level (the level of neuronal assemblies) is of milliseconds, while the spatial resolution is about a centimeter. Electroencephalography (EEG) and magnetoencephalography (MEG) are the only methods that satisfy simalteneously to both these time and space scales (Freeman et al., 2001). EEG/MEG detect fast changes in the gross synchronous activity of thousands of cells in selected areas on the cortical surface, thus collecting information from the relevant level of brain organization (Revonsuo, 2001). However, classical approaches to EEG/MEG analysis reveal only limited knowledge of what is going at the level of neural assemblies (Fingelkurts et al., 2005a). The main reason for that is that the studies are designed in a way that they avoid the temporal structure of the phenomenon under investigation. Recordings of brain activity are generally averaged over hundreds of repeated trials or more, in order to eliminate fluctuations in ongoing activity (the "noise") that are not correlated with stimulus presentation (for a critical discussion see Fingelkurts et al., 2002; Fingelkurts et al, 2003c). Thus, an additional question arises: Which

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[28] This is the self-organizing dynamic process (for the review see Fingelkurts and Fingelkurts, 2001).

[29] It is important to stress here, that complex OM does not have instructive power upon simpler OMs, it is just a new cognitive state in its own right.

[30] The property of abstractness gives particular advantages for adaptive behavior of the organism: If only a few signals from the relevant objects are available, categorical (abstracted) knowledge can allow for an adequate response to a wide range of stimuli and thus permit adaptive behavior (Edelman, 1987).

[31] See also Taylor (2002) for the view that consciousness can be regarded as created by suitably specific processes arising from the movement of attention.

of known EEG/MEG analysis approaches can derive the information about operations (discrete events) of neural assemblies and estimate the inherent temporal/dynamical correlations (functional connectivity) among them?

Estimation of Neuronal Assemblies

Neurons that constitute neural assemblies, sum their electrical fields in passing across the extracellular resistance, giving rise to extraneuronal potential differences manifested in the EEG, which correspond to the local field potentials (Freeman et al., 2001). The fact that neurons are able to synchronize their subthreshold oscillations (excitatory postsynaptic potential, EPSP and inhibitory postsynaptic potential, IPSP), leading to fixed states of an overall neuronal assembly and to rapid transitions between such states, was shown experimentally and in computational models (Makarenko and Llinas, 1998). Generally, the overall pattern of correlated activity is very sensitive to fluctuations and it may be swiftly rearranged during rapid shift (Kirillov and Makarenko, 1991; for review, see Singer et al., 1997). As it was demonstrated *in vitro*, the intervals of local fixed potentials are manifested in the oscillatory waves, which are the result of neuronal clustering (Leznik et al., 2002). At the EEG level these intervals are reflected in defined periods (segments) of *quasi-stationary activity*[32] (Fig. 3) operating in different frequency ranges (for review, see Kaplan and Shishkin, 2000; Kaplan et al., 2005). In this case, it is possible to consider one segment as the single event in EEG-phenomenology (Fingelkurts and Fingelkurts, 2001). Within the duration of one segment, the neuronal assembly that generates the oscillations is in the steady stationary state (Brodsky et al., 1999). The transition from one segment to another reflects the changes of the generator system microstate or changes in the activity of the two or more systems (Jansen et al., 1988; Kaplan and Shishkin, 2000). Thus, in order to detect such rapid transitions the task is to divide the EEG signal into stationary segments by estimating the points of transition. These instants within short-time window, when the EEG amplitude is changed abruptly, are identified as *rapid transition processes* (RTP) (Kaplan et al., 2005). RTP is supposed to be of minor length, and therefore can be treated as a point or near-point[33] (Fig. 3; see also Fingelkurts and Fingelkurts, 2001). The issue of segmental description of brain activity has been addressed by several researchers (for review see Barlow, 1985). However, virtually all such segmentation approaches have a number of inherent limitations (for a detailed review and discussion see Kaplan and Shishkin, 2000 and Kaplan et al., 2001).

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[32] Yet in 1972 year, it was experimentally shown in detail by Elul, that EEG is a product of (de)synchronized neurons within a cellular assembly (Elul, 1972a,b). EEG waves recorded from the scalp are integrated excitatory postsynaptic potentials (EPSP's) and inhibitory postsynaptic potentials (IPSP's) of neuronal membranes. Since they reflect extracellular currents caused by synchronized neural activity within the local brain volume (John, 2002), the EEG signal within quasi-stationary segments is the envelope of the probability of non-random coherence (so called a “common mode”) in the neuronal ensembles near to the recording electrodes.

[33] Note, that mathematically it is not important in which time-window the amplitude transition is estimated. What is important, – it is the speed of such transition. Experimentally it was found, that amplitude transition in the RTP area is always very rapid – not less than twofold, if comparison is made between amplitude values in the close area before RTP and immediately after it (Fingelkurts, 1998).

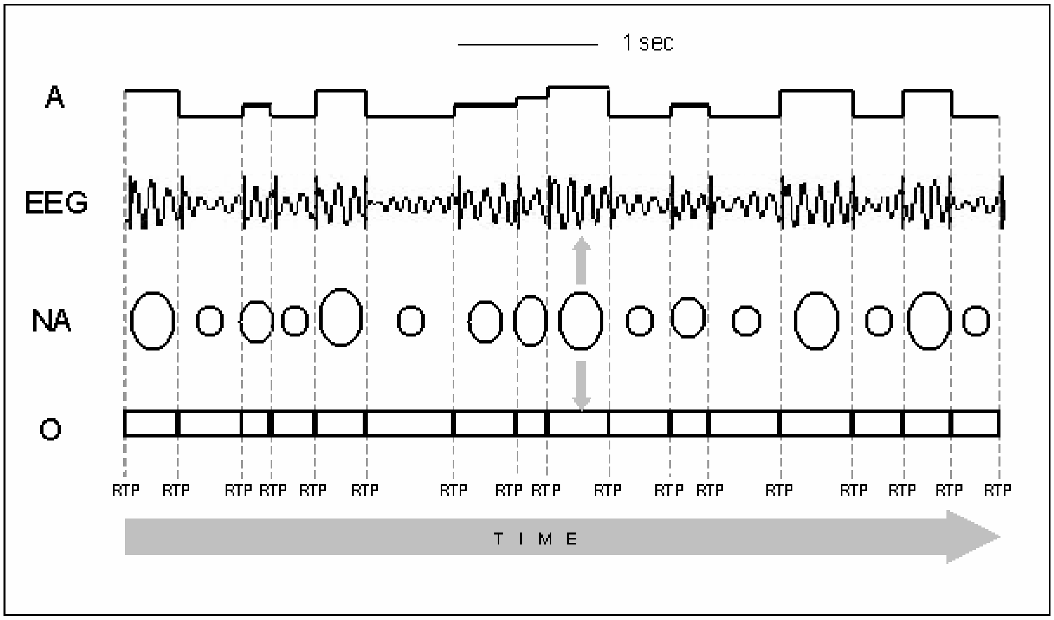


Figure 3. Correspondence between neuronal assemblies and EEG segments. *A*, amplitude of EEG segments; *EEG*, electroencephalogram; *NA*, neuronal assemblies of different size; *O* – operations of different duration; *RTP*, rapid transition periods (boundaries between quasi-stationary EEG segments).

To overcome the disadvantages of classical methods of segmentation, the novel technology of the adaptive *non*parametric EEG/MEG segmentation was developed (Kaplan et al., 1997; 2005). This method is performed in two stages (Fig. 4 A). The *first stage* is performed in two steps. During the first step, the native EEG/MEG values were converted into the module. Second step corresponds to the basic procedure of segmentation: The main idea is in comparison of the ongoing EEG/MEG amplitude absolute values averaged in the sliding *test*-window and EEG/MEG amplitude absolute values averaged in the sliding *level*-window (test window << level window). The duration of windows is short (6-800 ms) and dependent on the analyzed frequency range and sampling rate of the signal; the shift of both windows is equal to one data-point. The use of short time windows is motivated by the need for tracking non-stationary transient cortical processes on a sub-second time scale. As a result of averaging in sliding test- and level-windows, two new sequences (test – *t* and level – *l*) are constructed from the initial one, and are placed on the same time-scale (Fig. 4 A). The time-instants corresponding to the crossing of *t*- and *l*-time-series become a preliminary estimate of RTP.

The aim of the *second stage* is to estimate the statistically significant RTPs. For that the two conditions should meet (Fig. 4 B). First condition estimates the steepness of a change (Fig. 4 B, a): the EEG/MEG amplitude values are averaged at the *t*-time-series within *n* data-points before (M_{-n}) and after (M_{+n}) preliminary RTP. If the result of subtraction ($M_{+n} - M_{-n}$) is statistically significant (the Student criteria, $p < 0.05$ with coefficient 0.3), then this first condition is accepted and second condition should be tested. Second condition (Fig. 4 B, b) must be fulfilled in order to eliminate possible "false alerts" associated with anomalous peaks in the EEG/MEG amplitude. The five points of the digitized EEG/MEG following this preliminary RTP must have a statistically significant difference between averaged amplitude values in the *t*- and *l*- time-series (the Student criteria, $p < 0.05$ with coefficient 0.1). Only if these two criteria are met, the preliminary RTP is assumed as actual.

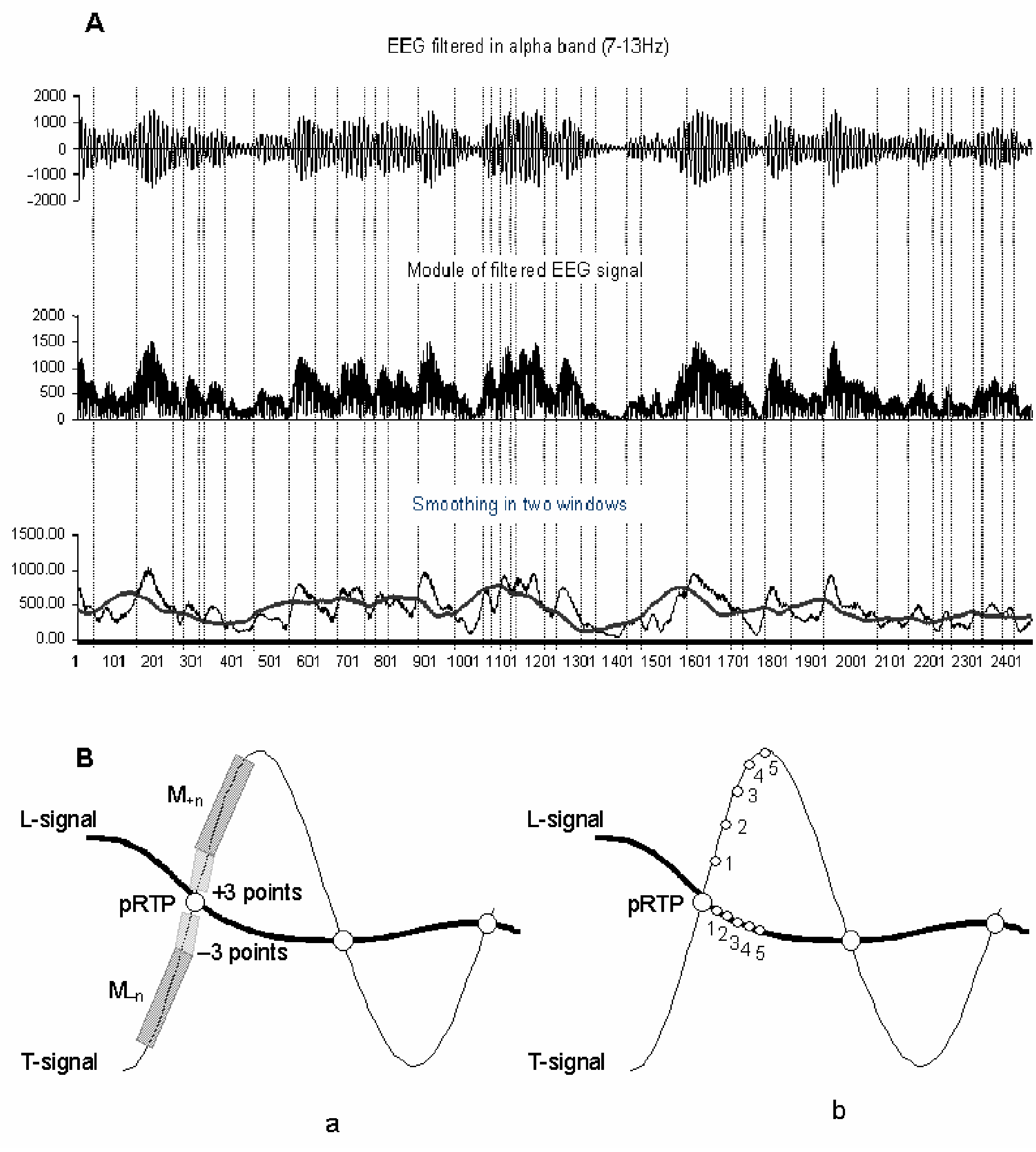


Figure 4. Nonparametric adaptive level segmentation of EEG/MEG (schematic presentation). *A*, First stage of segmentation (two steps). On the horizontal axis the data-points of digitized signal is shown. On the vertical axis the amplitude of the signal is shown in μV^2. Vertical dotted lines indicate the time coordinates of preliminary RTPs. *B*, Second stage of segmentation: two conditions for estimation the statistical significance of preliminary RTP (pRTP). Explanation in the text.

Using this technique, the sequence of RTPs with statistically proven ($p < 0.05$, Student *t*-test) time coordinates can be determined for each EEG/MEG location individually for each analyzed EEG/MEG epoch. RTPs or jumps in EEG/MEG amplitude in such a way are, in fact, the markers of boundaries between concatenated quasi-stationary segments. By varying the parameters of this technique it is possible to obtain the segments corresponding to a more or less detailed structure of the EEG/MEG. Therefore, there are prospects for the description of the structural EEG/MEG organization as a hierarchy of segmental descriptions on different time scales (Kaplan and Shishkin, 2000). The modeling experiments and theoretical concepts behind this analysis are described elsewhere (Kaplan, 1998; Kaplan and Shishkin, 2000; Fingelkurts et al., 2005; Kaplan et al., 2005).

After quasi-stationary segments (indexed by RTP) are obtained, several characteristics (attributes) of segments (Kaplan and Borisov, 2003) can be calculated separately for each channel (Fig. 3):

1. Average amplitude (*A*) within each segment (μV^2) – as generally agreed, indicates mainly the volume or *size of neuronal population*.
2. Average length (*L*) of segments (ms) – illustrates the functional life span of neuronal population or the *duration of operations* produced by this population.
3. Coefficient of amplitude variability (*V*) within segments (%) – shows the *stability of local neuronal synchronization* within neuronal population or assembly.
4. Average amplitude relation (*AR*) among adjacent segments (%) – indicates the neuronal assembly behavior – growth (*recruiting of new neurons*) or distraction (*functional elimination of neurons*).
5. Average steepness (*S*) among adjacent segments (estimated in the close area of RTP) (%) – reflects the *speed* of neuronal population growth or distraction.

The comparison of the same segment attributes between different experimental conditions or functional states is performed using Wilcoxon matched pairs *t*-test. These attributes reflect different aspects of local processes in the cortex and thus permit assessing the mesolevel description of cortex interactions (interactions within transient neuronal assemblies) through large-scale EEG/MEG estimates (for experimental support and detailed discussion see Fingelkurts et al., 2004b; Kaplan et al., 2005).

Estimation of Functional Connectivity and/or OM

Considering that complex cognitive operations arise from combined synchronous operations of many neural assemblies, the measure of functional connectivity should be capable to estimate such synchrony. Traditionally, coherence and correlation have been the main methods to assess the degree of functional connectivity between brain areas (Thatcher et al., 1986). Recently, several new methods for detecting functional connectivity between cortical areas have been introduced: Partial directed coherence (Baccala and Sameshima, 2001), dynamic imaging of coherent sources (Gross et al., 2001), structural equation models for fMRI (Friston and Buchel, 2000), and phase synchrony (Tass, 1999). However, all these methods have several limitations (for a discussion, see Fingelkurts et al., 2005a).

The novel approach overcomes the disadvantages of conventional methods, and can reveal inherent functional interrelationships between cortical areas different from those measured by correlation, coherence and phase analysis (for a discussion and modeling experiments see Kaplan et al., 2005; Fingelkurts et al., 2005a).

The technology for estimation of functional brain connectivity through the index of EEG/MEG structural synchrony (ISS) is as follows. Each rapid transitional process (RTP) in the *reference* EEG/MEG channel (the channel with the minimal number of RTP from any pair of EEG/MEG channels) is surrounded by a short "window" (ms). It is taken that any RTP from another (*test*) channel coincided if it fell within this window. The ISS for pairs of EEG/MEG channels can be estimated using this procedure. The ISS is computed as follows:

$$\mathbf{ISS} = \boldsymbol{m}_{windows} - \boldsymbol{m}_{residual},$$

$$\text{where} \quad m_{windows} = 100 * \frac{sn_w}{sl_w}; \; m_{residual} = 100 * \frac{sn_r}{sl_r};$$

sn_w – total number of RTPs in all windows (window for synchronization) in the test channel;

sl_w – total length of EEG/MEG recording (in data points) inside all windows in the test channel;

sn_r – total number of RTPs outside the windows (window for synchronization) in the test channel;

sl_r – total length of EEG/MEG recording (in data points) outside the windows in the test channel.

It is obvious, however, that even in the absence of any functional interrelations between EEG/MEG locations there should be a certain stochastic level of RTPs coupling, which would reflect merely occasional synchrony. The values of such stochastic inter-location relations should be uniform and substantially lower than in the actual presence of functional interrelation between different of EEG/MEG channels. Because of unknown statistical properties of the RTPs coincidence, the construction of thresholds is necessary. The time-variant thresholds were established by the use of surrogate data**.** Thus, to arrive at a direct estimation of a 5% level of statistical significance of the ISS ($p < 0.05$), computer simulation of RTP's synchronization is undertaken based on random shuffling of time segments marked by RTPs (500 independent trials). These share the properties of the experimental data (number of RTPs in each EEG/MEG channel of analyzed pair, number of segments, and number of windows of synchronization), but the time coordinates of RTPs were altered randomly in each trial so as to destroy the natural temporal structure of the data. Justification for this approach can be found in Fingelkurts et al. (2004a). However, other approaches are also possible (see for example Bullmore et al., 2001).

As a result of 500 times repeated random reshuffling of the time segments marked by RTPs the stochastic level of RTPs coupling (ISS_{stoh}), and the upper and lower thresholds of ISS_{stoh} significance (5%) are calculated. These values represent an estimation of the maximum (by module) possible stochastic rate of RTPs coupling (confidence levels). Only those values of ISS which exceeded the upper (*active coupling*) and lower (*active decoupling*) thresholds of ISS_{stoh} have been assumed to be statistically valid ($p < 0.05$). Thus, the ISS tends towards zero where there is no synchronization between the EEG/MEG segments and has positive or negative values where such synchronization exists (Fig. 5). Positive values indicate 'active' *coupling* of EEG/MEG segments (synchronization of EEG/MEG segments is observed significantly more often than expected by chance), whereas negative values mark 'active' *decoupling* of segments (synchronization of EEG/MEG segments is observed significantly less than expected by chance). From a qualitative perspective, the coupling of EEG/MEG segments corresponds to the phenomenon of synchronization of brain operations or *Operational Synchrony* – OS (for review, see Fingelkurts and Fingelkurts, 2001, 2003).

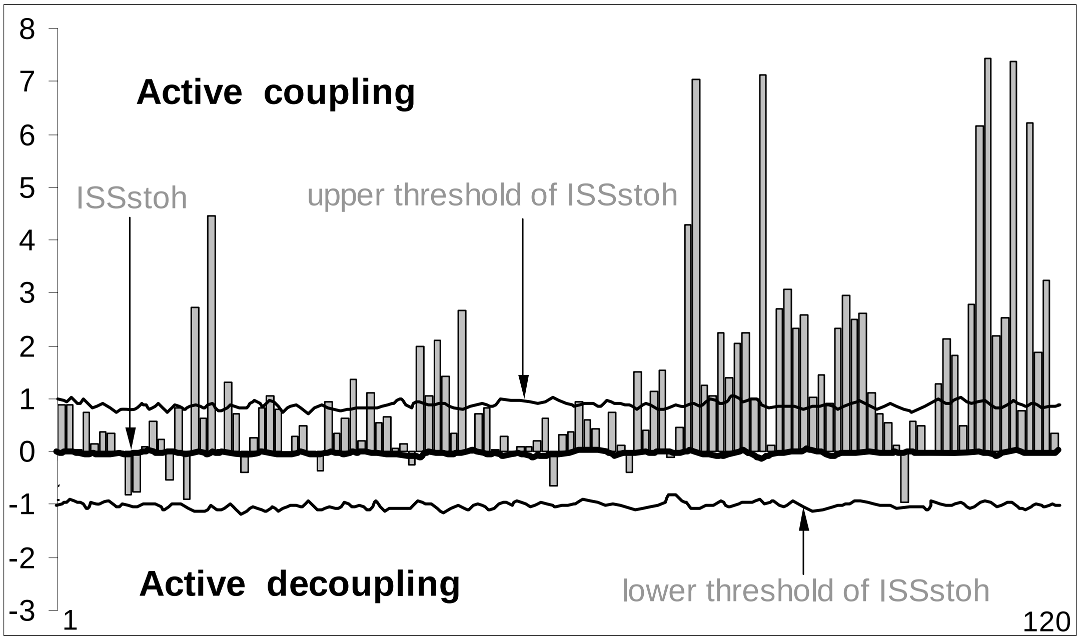


Figure 5. Schematic illustration of the index of structural synchrony (ISS) and its stochastic levels. As an example, the calculations of ISS are shown for 16 EEG channels. The *Y*-axis displays the ISS values found in the experiment (illustrated as gray bars). The *X*-axis displays the 120 possible pair combinations of 16 EEG channels (1 = O1-O2, 2 = O1-P3, 3 = O1-P4, 4 = O1-T5, … 115 = F4-Fz, 116 = F4-F7, 117 = F4-F8, 118 = Fz-F7, 119 = Fz-F8, 120 = F7-F8). Figure is reproduced from the Fingelkurts et al. 2004, Human Brain Mapping ©.

It is obvious also that there should be the synchronization of segments in a more than two EEG (or MEG) locations, assuming that same set of neuronal assemblies may co-operate in different combinations along the execution of a cognitive and mental acts (Fingelkurts and Fingelkurts, 2003, 2004). Thus, transient synchronization of brain operations (indexed by structural synchrony in EEG/MEG) going on in several cortical areas would construct a so-called *operational module* (OM) (Kaplan, 1995; see also Fingelkurts and Fingelkurts, 2001; for experimental support see Fingelkurts et al., 2003a; 2004b), which constitutes the unified and metastable neural state (for a detail see Fig. 2 and the previous section of this Chapter). OM means that the set of the neuronal assemblies synchronously participated in the same cognitive act during the analyzed period. The criterion for defining an OM is a sequence of the same *synchrocomplexes* (SC). Whereby, SC is a set of EEG/MEG channels in which each channel forms a paired combination (high values of ISS) with all other EEG/MEG channels in the same set (Fig. 6); meaning that all pairs of channels in an SC have to have significant index of structural synchrony (Fingelkurts et al., 2003a; 2004b; see also Fingelkurts and Fingelkurts 2003).

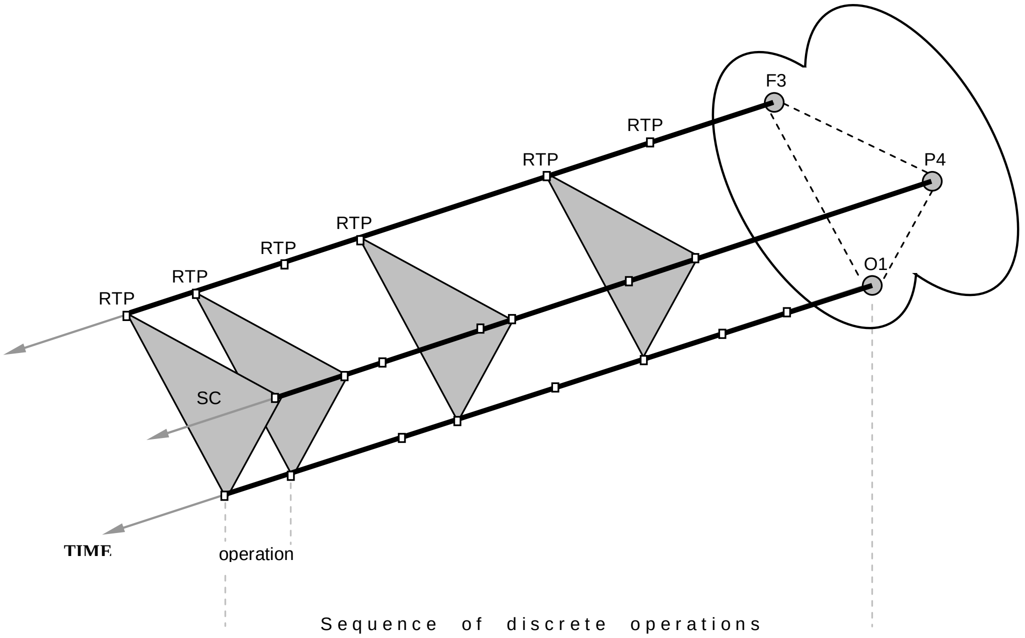


Figure 6. Estimation of OM. *RTP*, rapid transition periods, – are the boundaries between EEG/MEG quasi-stationary segments (at electromagnetic level) and the boundaries between neural operations (at the phenomenological level). F_3, is the left frontal area; P_4, is the right parietal area; and O_1, is the left occipital area. Only neural assemblies in these areas synchronize their operations on a particular time-scale. *SC*, momentary synchrocomplex, – the synchronization of RTPs between different local EEG/MEG at a particular moment.

The result of structural synchrony measure is automatically drowned upon computer OS maps (Fig. 7). The changes in operational synchrony maps should only considered relevant if these changes appeared consistently in a majority of the trials and subjects (not less than 85% of occurrence) under the experimental conditions being analyzed. This permits to overcome the common problem of multiple comparisons between maps that exists due to the large number of electrode pairs in the maps (Rappelsberger and Petsche, 1988).

It was demonstrated, that the metastable topological combinations in the EEG/MEG field do exist (Fig. 7) and appeared to be correlated with and dependent on the subjects' individual level of anxiety (Shishkin et al., 1998), cognitive tasks (Fingelkurts et al., 2003b), multisensory perception (Fingelkurts et al., 2003a), and on the pharmacological influence (Fingelkurts et al., 2004a,b), large ontogeny shifts (differences between children and adults) (Borisov, 2002), and on the changes in the functional state of the brain during schizoid diseases (Kaplan and Borisov, 2002). These data not only increase our knowledge about fundamental brain mechanisms, but also provide sensitive indexes which can serve as additional diagnostic markers of some psychiatric and brain disorders (Fingelkurts et al., 2005b).

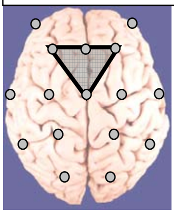
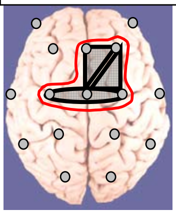
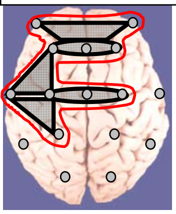
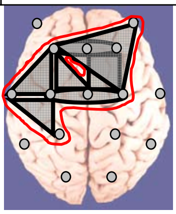
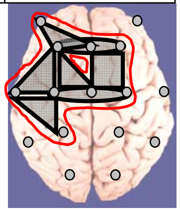
Phenomenal level	**Rest**	**Waiting**	**Encodin**	**Keeping in mind**	**Retrieval**
Electro-physiological level					
Number of simple OMs	1	3	5	7	7
Number of complex OMs	0	1	1	1	1
OM's complexity	increases				

Figure 7. Isomorphism between functional structures of phenomenological experience and electromagnetic brain field. Phenomenological level illustrates the ever-changing stream of cognitive acts (in limit, thoughts or images) where each momentarily stable pattern is a particular cognitive operation. Thus, stream of phenomenal experience has a composite structure: It contains stable nuclei (or cognitive operations/thoughts/images) and transitive fringes (or periods). At the EEG/MEG level these processes are reflected in the chain of periods of short-term metastable states (or operational modules – OM) of the whole brain and its individual subsystems (grey shapes), when the numbers of degrees of freedom of the neuronal networks are maximally decreased. Red shapes illustrate complex OMs. Changes from one cognitive act to another are achieved through rapid transitional periods. Experimental data are presented from the experimental study by Fingelkurts et al., 2003a.

CONCLUSION

This Chapter outlines the Operational Architectonics (OA) framework of brain and mind functioning (Fingelkurts and Fingelkurts, 2001) with emphasis on neuronal assemblies and their operations (mesoscopic level). This framework captures a strong intuition about the brain mechanisms that constitute perception, cognition and consciousness. Practical methods of imaging the mesoscopic level of brain organization were described. These methods allow analyzing with an incredible detail the operational behavior of local neuronal assemblies and their joint activity in the form of unified and metastable operational modules. We argue that the level of brain organization revealed by these methods corresponds to the phenomenal level of cognition and consciousness.

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