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OPERATIONAL ARCHITECTONICS OF PERCEPTION AND COGNITION (A PRINCIPLE OF SELF-ORGANIZED METASTABLE BRAIN STATES)

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Abstract
Recent neuroscience theories state that cognitive percepts result from the integrative activity of functionally specialized brain areas, however the experimental data still tend to be discussed in the terms of activated local areas. Most likely the reason for that is a lack of consistent theory and understanding of the mechanisms through which the brain orchestrate the symphony of perceptions, thoughts and actions. The aim of this paper is to contribute to an understanding of such mechanisms. The concept we offer has several more-or-less polemic hypotheses grounded in rather well-established facts. Not all the hypotheses are originally our own, but the aggregate presented here is novel and provides a sound framework for understanding important aspects of the brain mechanisms that constitute perception, cognition and consciousness.

The global principles of coding and representing in human brain the environmental scenes and objects, in particular the relations of these representations to mental states and thoughts are still an enigma for modern science. As to visual modality (being the best investigated) there is a somewhat general agreement that a particular percept emerged in a result of a specific spatial-temporal pattern of neuronal activity in different brain (neocortex) areas which represent specific features of objects or scenes. However the exact mechanism of emergence and regularities of such neuronal activity patterns are still far from being understood.

To come closer in understanding of these processes it was suggested the concept of **Operational Architectonics**[1] (Fingelkurts & Fingelkurts, 2001) of brain activity, where:

1. The single neurons (highly distributed along the cortex) can quickly become associated (or dis-associated) by synchronization of their activity giving rise to *transient assembles*. Each of these functional assembles represent discrete elemental brain *operations* some of which process different attributes of object or environmental scene.
2. The temporal synchronization of such brain operations together (*Operational Synchrony* – OS) gives rise to a new level of brain abstractness – metastable brain states. These metastable brain states or functional *Operational Modules* (OM), as we name them, may underlie the cognitive percepts and mental states which have representational nature. The sequence of these metastable OMs thus represents the stream of thoughts.
3. OMs may be further operationally synchronized (on other temporal scale) to form new OMs of even larger abstractness from the initial brain state. In the limit, such process may lead to the generation of the most complex mental state, which corresponds to the personal self.
4. Also the reverse process is possible – when complex mental state guided by attention is decomposed to several simpler mental states which in their turn may be further decomposed.

Below we will discuss each of these points in detail, however firstly we should address the central notion of our concept – *'operation'*.

What dose the term 'operation' refers?

We used the broad definition of this term: operation is a basic process that applies to an operand and yields a transform (Krippendorff, 1986). It should be stressed that this is so regardless of whether this process is conceptual or physical. In fact everything which can be represented by a process, is an operation. This provides a basis for discussion of the relative complexity of operations. In this sense the activity of single neuron is the sequence of elemental simple operations; the activity of neural assemblies within the same brain area constitutes the sequences of a more complex

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

operations; the joint activity of neural assemblies within many brain areas underlie even more complex operations or operational acts. Somewhere here there is a shift from brain (physical) operations to cognitive (conceptual) operations[2] (McIntosh, 1999). Thus, the complex operation or operational act has internal structure where each element in its turn also has its own internal structure and so on until the simplest elemental operation is reached. What we want to argue here is that there is a more complex operation/operational act that subsumes the simplest ones. But what is important here is that any complex operation/operational act is not just a conjunction of simplest operations (or operational acts) – it is an operation (or operational act) in its own right with emergent properties that are not evident in the subordinate constituents (McIntosh, 2000).

This description has seemed to be so trivial that one may wonder whether anything really interesting can be expressed with it. However, understanding of the *operation as a process*[3] (being central for brain functioning) and considering its *combinatorial nature*, seems especially well suited for describing and studying the mechanisms of how information about the 'objective' physical entities of the external world can be integrated, and how unified/coherent mental states can be established in the internal entities of distributed neuronal brain systems (Fingelkurts & Fingelkurts, 2001). To get a better insight into the meaning of the 'operations' and 'operational process', lets consider each of the points stating in the beginning of this paper.

(1) Transient Neural Assemblies

Large experimental work suggests that the neural assemblies provide a framework for the integration of distributed brain activity (Palm, 1990; Eichenbaum, 1993; von der Malsburg, 1999; Varela et al., 2001). Here the emphasis is put not on the anatomical neural networks (as they understood in classical concepts – Hebb, 1949; Hayek, 1952), but rather on the functional brain units or assemblies (von der Malsburg, 1999). It is supposed that large neuronal populations can quickly (abruptly) become associated or disassociated thus giving rise to transient assemblies (Triesch & von der Malsburg, 2001). The emergence of specific neural assemblies is thought to serve as the functional elements of brain activity (Kaplan & Borisov, 2003) thereby

[2] Neural assembly may be 'critical' for a particular operation, however the cognitive operation itself arises from combined actions/operations of many neural assemblies (McIntosh, 1999).

[3] For our further reasoning it is important to emphasize that the view we are standing by is that the thought is not a thing, but rather a process (James, 1890; Edelman & Tononi, 2000; Edelman, 2001).

executing the basic operations of informational processing (Finger, 1994; McIntosh, 1999; Varela et al., 2001). Here assembly as a whole stands for the combined operation which results in a coherent pattern that 'represents' a particular content, whereby each of the participating neurons is tuned to only a subset of the elementary features of composite perceptual (or mental) object, or environment scene (McIntosh, 2000; Singer, 2001). The communication of neurons within the assembly is achieved through the synchronous operations executed by each neuron[4] (Abeles, 1991; Singer, 1993). It is well documented that neurons in both cortical and subcortical units can synchronize their activity with a precision in the millisecond range (Gray & Singer, 1989; Engel et al., 1997, 1999; Singer et al., 1997; Singer, 1999; Wright et al., 2000). 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 & Singer, 1997). It is supposed that this process relay on self-organization (Singer, 2001) where the role of dendrites is crucial (Ryder & Favorov, 2001).

Generally neural assemblies (or populations) have defined as distributed group of neurons or neural masses for which correlated activity persists over substantial time intervals (Nunez, 2000). It is suggested that this time interval is required to accomplish an elementary brain operation (Varela et al., 2001). At the EEG (or EMG) level[5] these time intervals are reflected in the periods of the quasi-stationary activity within different frequency ranges (Fingelkurts & Fingelkurts, 2001). Exactly such segments of quasi-stationarity can be assessed through adaptive segmentation procedure[6] (Kaplan et al., 1997; Kaplan & Shishkin, 2000; Fingelkurts & Fingelkurts, 2001).

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[4] The interspike interval is the joint property of two arrival times, and as such it is inherently a relational entity (process/operation) rather than an absolute event-in-itself. It should be noted that while the spikes that mark up an interspike interval are discrete events, the interval itself could vary in a continuous manner. Thus interspike interval codes are analog codes. This makes them suitable for conveying a continuous range of possible values (Cariani, 1997).

[5] EEG is that level of organization where the nervous system organize itself into functionally and behaviorally relevant units which is remarkably correlated with cognition (Fingelkurts & Fingelkurts, 2001). Indeed the level of organization at which cognition, mind and "consciousness resides might be a highly organized macro-level electrophysiological phenomenon in the brain, realized by the coordinated electrical activity of specific populations" (Revonsuo, 2001, p. 5).

[6] Also several characteristics (attributes) of segments (Kaplan & Borisov, 2003) could be assessed: *average amplitude* within each segment – indicates the volume of neuronal population; *average length* of segments – illustrates the duration of operations or the functional life span of neuronal population; *coefficient of amplitude variability* within segments – shows the stability of neuronal synchronization within neuronal population; *average amplitude relation* among adjacent segments –

(2) Operational Synchrony and Operational Modules

Different brain operations executed by different neuronal assembles tend to be synchronized if they happens to be at the same time, thus related to the same perceptual/cognitive act (Cleeremans, A., 2002). Since the multivariability of the brain is huge (Kaplan & Shishkin, 2000), the number of combinations of possible brain states is also very high (Bressler & Kelso, 2001). Qualitatively such kind of synchronization of operations refer to the *Operational Synchrony* (OS) whereas quantitatively such phenomenon is assessed through the measure of synchronization of EEG segments (*Structural Synchrony* – SS) obtained from different brain areas (Kaplan et al., 1997; Fingelkurts, 1998; Kaplan & Shishkin, 2000; Fingelkurts & Fingelkurts, 2001; Fingelkurts et al., 2003).

In the result of OS process, the metastable brain states are emerged which accompany the realization of brain complex macrooperations[7]. These metastable brain states (when the number of degrees of freedom of the neural networks are maximally decreased) constitute the *Operational Modules* (OM), which we supposed to accompany *mental states*[8] (Fingelkurts & Fingelkurts, 2001). The key point here is that OMs have a more complex structure than operations which constitute them. However OMs carry less fine-grained information since only the essential information for the emergent cognitive percept or act is preserved. For example, in the case of visual perception, large amount of information (intensity of the stimulus, lightness, color, shape, size, proximity, texture and so on) is represented and processed by sensory receptors, singular neurons and neural assemblies, however at the higher level of abstractness (metastable OMs) the image of 'cat', for instance, is presented. Thus, in accordance with the information theory of Shannon (1948)[9], the OS process

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indicates the direction of neuronal population growth or distraction; *average steepness* among adjacent segments – shows the speed of neuronal population growth or distraction.

[7] The importance of OS process for the perceptual grouping and for the 'normal' cognitive operational acts was shown experimentally. Subjects, which do not have audio-visual integration (Fingelkurts et al., 2003) or failed to memorize the visual image (Fingelkurts, 1998), showed the negative OS process, meaning that the particular brain areas actively unsynchronized their operations. Note, that the suppression of interactions between cortical areas is not achieved by inhibition responses, but by a sufficient degree of temporal dis-coordination of operations (see Fingelkurts et al., in submission a,b).

[8] Of course, not every OM constitutes a mental state. 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 data anymore.

[9] According to this concept the information carried by a system is said to characterize the abstractness of system states selected out of an ensemble of many differing possibilities. See also Chalmers (1996)

'abstracts out' the information carried by OMs, meaning that OMs are not sensitive to the original raw data anymore, but only to the spatial-temporal pattern of activation that embodied in the involved neuronal assemblies. So the information that remains is only an abstraction of certain aspects of the original data (Chalmers, 1996), including physical (non-mental) processes in the brain. Arbib (1981) came to the same conclusion in his theory of schemas as functional brain units, which provide the basis for the more abstract schemas that underlie thoughts (Arbib, 1989). Put simply, he states that mental state or thought is a gross abstraction of the brain state, where much of brain state information is not transparent for the mental state (Arbib, 2001).

If the metastable OMs constitute the mental states and if these states become conscious, then a large amount of knowledge that is not in stimulus *per se* can be extracted from the abstracted mental image (Revonsuo, 1999; Millikan, 1999): for example a the case of 'cat', cat now is silent, but you already know how it sounds. This phenomenon referred as a 'stream of thoughts'[10] (James, 1890; see also Mangan, 1993a,b; Chafe, 1994; Galin, 1994, 2000). The possible isomorphism (O'Brien & Opie, 1999a) between the structure of electrical brain field (EEG) presented as a sequences of metastable OMs on different time-scales (frequency oscillations) and the phenomenal structure of consciousness presented as 'stream of thoughts' have been suggested in Fingelkurts & Fingelkurts (2001). Assuming our hypothesis that OMs may represent the mental states or thoughts, one can see that the structure of electrical brain field[11], 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[12]) separated by rapid transitive processes (abrupt changes of OMs, cognitive acts or thoughts). For justification of this point of view see (Fingelkurts & Fingelkurts, 2001; for similar ideas see also O'Brien & Opie, 1999b).

(3) The Hierarchy of Metastable OMs

Before we will go on to elaborate this point, it might be useful to clarify our usage of the word '*hierarchy*'. By 'hierarchy' we mean the increasing complexity

for developing this concept to an information abstract state with relational and/or combinatorial structure.

[10] 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).

[11] May be reconstructed directly from EEG data.

[12] The most modern theory of consciousness (quantum coherent superposition state) also suggests that consciousness is a sequence of discrete events/processes (Hameroff, 2001).

levels, however in contrast to a systems view of levels, we assume that whatever happens at a lower level, it becomes permanently embodied in the level above and thus continues to influence this upper level regardless of how abstract this level appears to be (Narmour, 1992). To start with, recall that at any given moment, a subject has a multiple experiences. (S)he might simultaneously have visual, auditory, bodily and emotional experiences, and at the same time having the stream of thoughts. Even though each of these experiences is quite distinct from each other and can be perceived separately, it seems that all of them are unified, being part of a single mental (conscious) state (Bayne & Chalmers, 2002).

In the framework of our concept, we bring the hypothesis that OMs (being by themselves the result of synchronized operations going on in distributed brain structures and process different sensory modalities) could be operationally synchronized[13] between each other (on new time scale), thus forming more abstract and more complex OM which constitute new integrated experience (Fingelkurts & Fingelkurts, 2001; this idea coheres with O'Brien & Opie, 1999b). We supposed that each of the new OMs is not just a sum of simpler OMs. Rather, the more complex OM (^{c}OM) is most naturally a union of abstractions about simpler OMs (^{s}OM). Formally it can be presented as ^{c}OM forms kind of abstraction or statistical average about the ^{s}OMs representing what it is to be average abstraction[14]. At the same time this new ^{c}OM may also be ^{s}OM in its own right for higher level of abstractness and might be unified with other ^{s}OM to form new ^{c}OM[15]. Thus, subjectively we may feel that our visual, auditory, perceptual, bodily, emotional, cognitive and other experiences are unified. This so-called ‘singularity behind the multiplicity’ (Bayne & Chalmers, 2002) or fractality[16] could provide the plausible model of perception and cognition

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

[14]Time structure would be the organizing currency of the system. Time structure would be preserved in sparse form, distributed over OM^{s}. Information processing would be statistically-mechanical in nature, implementing temporal binding of operations on the all-order interval statistics of larger OM^{c}. Thus, functionally, the outcome of coincident operations is a spatial-temporal pattern (OM^{c}) rather than ensembles of particular neurons firing in synchrony (Cariani, 1997).

[15]In this interpretation, the “transition” of the same neural assembly (or brain area) into the new OM, in accordance with participation in the realization of another functional program, 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 & Fingelkurts, 2001; Fingelkurts et al., 2003).

[16]Mandelbrot coined the term fractals (see Buchanan, 2000). He discovered that many processes often look roughly the same when viewed at different levels of magnification, i.e., the same patterns are repeated on many different scales. This feature of fractals is termed self-similarity or scale-

organization. Since at the top level of abstractness (consciousness) we already do not have direct access to the brain processes, the subjective (conscious) experience seems so strange to us (Chalmers, 1996). Notice that the externally induced and internally generated OMs are virtually indistinguishable. It indicates that the process of operational synchrony (OS) is a universal principle for perception, cognition and phenomenal experience (Fingelkurts & Fingelkurts, 2001)[17].

The basic prediction of this framework is the existence of a practically infinite hierarchy of experiences. On the top of such infinite hierarchy there should be the maximal mental (conscious) state representing and abstracting all the underneath subjective experiences for a given moment of time[18]. Here it is worth to note that if the ^{s}OMs representing 'component figures' get operationally synchronized into new ^{c}OM then the 'big figure' is experienced subjectively, but there are no experiences about 'component figures', since component ^{s}OMs are not represented anymore.

The important point: considering the composite polyphonic character of the electrical (EEG) brain field, this field may be presented as a mixture of many time-scale processes (individual frequency components) (Nunez, 2000). Consequently, a large amount of functionally distinct OMs can co-exist simultaneously on different time-scales and even between them[19] (Fingelkurts, 1998; Kaplan & Shishkin, 2000; Fingelkurts & Fingelkurts, 2001). Altogether these OMs exist simultaneously[20] to subserve the operational acts on the functioning of the organism and on the interaction of the organism with its environment (Arbib, 2001). Some of these OMs may constitute the mental states. Thus, there are many mental images active at any time, however consciousness is rather *focused* to a particular mental state[21] (Fingelkurts & Fingelkurts, 2001), which can be of different complexity.

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invariance. The core discovery was that self-similar patterns in time and space are a consequence of each other (see also the definition of hierarchy in the beginning of this section).

[17] Note also that the same process of OS accompanies the brain (non-mental) functioning on the lower level of physiological processes (Fingelkurts & Fingelkurts, 2001).

[18] Most likely these moments of time correspond to the scale of seconds (Pöppel, 2002).

[19] Here there are no restrictions for the relations between frequency bands, because the method we used for assessing the OMs is not associated with the phase relation as the usual techniques estimating synchrony (Kaplan and Shishkin, 2000).

[20] If signal types can be encoded in characteristic spatial-time patterns (OMs) that serve as temporal 'stamps', then different kinds of time patterns (OMs) can be present/sent over the same transmission lines, at different times or even interleaved together without being functionally confused (Cariani, 1997).

[21] This point has been emphasized many times during history of psychophysiology science as 'limited capacity of conscious state' (Kahneman, 1973; Posner, 1987; von der Malsburg, 1997).

(4) Decomposition of OMs

The overall framework described here suggests that the brain functioning may be best conceptualized in terms of mixed continuity-discreteness[22]. Indeed, the OMs have many of the advantages of both traditional symbolic logics (Fodor & Pylyshyn, 1988; Fodor & McLaughlin, 1990) and distributed connectionist ones (Churchland & Sejnowski 1992). OM production is distributed across many neural assemblies, like in a connectionist network, yet the specific time patterns (OMs) themselves are unitary, like symbols of classical logics. Complex OMs thus could conceivably implement many of the same kind of multidimensional, multivalent logics which begin to be actively explored in cognitive science.

For instance, in the case of well-known example with 'John', 'loves' and 'Mary' the correspondent OM for complex idea like 'John loves Mary' can be constructed that do not contains any explicit representation of it parts – 'John', 'loves' and 'Mary' (Smolensky, 1991). Recall that each OM is abstractness from its constituent parts (see above). However, the information about the constituents can be extracted from the representations (Chalmers, 1990) by a sequential scanning of mental image or thought. Hence, the ^{c}OM could be decomposed to ^{s}OMs each of which would give rise to distant experience – either 'John', 'loves' or 'Mary', or some combination of them, like 'John loves'. 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[23].

Singer (2001) suggests a particular mechanism of how attention can guide synchrony. In our adaptation for operational synchrony (OS) process it may be presented as follows: Attention could impose a OS threshold modulation on neural assemblies that need to participate in the execution of a particular cognitive or behavioral act and thereby permits rapid synchronization of selected operations using the OS mechanism described in the Section 2. Thus, attention acts like a dynamic filter that accomplished the rapid required (un)grouping and temporal (un)binding of neural assemblies operation (Singer, 2001).

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[22]Presented framework suggests also that both parallel and serial processing may be just different sides of the same one mechanism - OS. Parallel processing is performed by individual neuronal assemblies and serial processing emerges as a result of formation of OMs and their shifts between interesting objects (in the physical or mental world), which they represent.

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

Conclusion

This paper is a step further in development of our Operational Architectonics (OA) concept of brain functioning (Fingelkurts & Fingelkurts, 2001). We were not aim here to conclusively prove it, however we aimed to show that this concept is plausible, and that it captures a strong intuition about the brain mechanisms that constitute perception, cognition and consciousness.

Presented here an OA concept can be mathematically formulated within the framework of combinatorial-state automata (CSA) proposed by Chalmers (1994). CSA differ from the finite-state automata (FSA) in that its *internal state* is not monadic (meaning the lack of internal structure), but has a complex structure (being a vector). The elements of this vector can be thought of as the components of the overall state. There are a finite number of possible values for each element. These values can be thought of as 'microstates'. Internal state vectors can be either finite or infinite. Even if a CSA lacks of input and output (modeling of mental activity, for example, during thinking or sleep), its combinatorial structure provides the condition for functioning (for detail see Chalmers, 1994).

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