Below is the unedited draft of the article that has been accepted for publication
(© Cognitive Processing, 2006, V. 7. No 3. P. 135-162)

Timing in Cognition and EEG Brain Dynamics: Discreteness versus Continuity

Andrew A. Fingelkurts and Alexander A. Fingelkurts

BM-SIENCE – Brain and Mind Technologies Research Centre, PO Box 77,
FI-02601, Espoo, Finland

Abstract: This article provides an overview of recent developments in solving the timing problem (discreteness *vs.* continuity) in cognitive neuroscience. Both theoretical and empirical studies have been considered, with an emphasis on the framework of Operational Architectonics (OA) of brain functioning (Fingelkurts and Fingelkurts, 2001, 2005). This framework explores the temporal structure of information flow and interarea interactions within the network of functional neuronal populations by examining topographic sharp transition processes in the scalp EEG, on the millisecond scale. We conclude, based on the OA framework, that brain functioning is best conceptualized in terms of continuity-discreteness unity which is also the characteristic property of cognition. At the end we emphasize where one might productively proceed for the future research.

Keywords: Temporal structure; Consciousness; Cognition; Perception; EEG; Discreteness; Continuity; Operational Architectonics; Brain operations; Large-scale networks; Metastability; Synchronization; Binding Problem; Brain and Mind.

1. Introduction

There has been an accumulation of phenomenological and experimental evidence that the *temporal structure* of cognition and of activity of its neural substrate is the key intrinsic attribute of perceiving and processing information (Dennett and Kinsbourne 1995; Pöppel 1997; Glicksohn 2001). Nevertheless, without a clear understanding of the nature of such temporal structure, it is hard to determine the temporal relations among various cognitive processes. One important question concerning the possible nature of the temporal structure of information processing is the following: Does each cognitive process produce a discrete packet of information, or is the flow of information continuous? Indeed, at any given moment, an individual has many distinct phenomenological experiences, which seem to be *continuously* unified and evolving (Bayne and Chalmers 2002); in the normal and awake mind the objects of thought are continuously being represented (Damasio 2000). At the same time, the individual has a stream of *discrete* conscious units – thoughts or images (James 1890; see also Mangan 1993a,b; Chafe 1994; Galin 1994, 2000). Given such conflicting everyday observations, it is difficult to reach a firm conclusion about the temporal structure of information processing. This apparent dual nature of information processing requires an explanation in a complete scientific account of consciousness and brain processing.

The temporal properties of individual neurons and of neuronal assemblies/populations have been postulated to underlie key visual (Bair 1999), motor (Baker et al. 2001), sensoriomotor (Crone et al. 1998), audio (Galambos et al. 1981) and audiovisual (Fingelkurts et al. 2003a) processes, as well as memory (McIntosh 1999; Fingelkurts et al. 2003b), perception (John 1990), attention (Reynolds and Desimone 1999), and other cognitive functions. However, the temporal aspects of the neural representations of cognition have not been systematically addressed. One of the reasons for this ignorance is hidden in the experimental paradigms (VanRullen and Koch 2003). Most current 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 so-called "noise") that are not correlated with stimulus presentation (for critique of averaging procedures, see Fingelkurts et al. 2002, 2003c). PET and fMRI maps, post-stimulus time histograms from single-cell or multi-unit recordings, as well as "evoked potentials" from EEG, which represent the majority of today's data on neuronal activity, are all based on this averaging principle (VanRullen and Koch 2003). As a consequence of such experimental paradigms, considerable uncertainty still remains about the temporal properties of human information processing.

The fundamental question in cognitive neuroscience of whether cognition and its neural representations occur in *discrete* epochs or *continuously* has not yet been definitely answered one way or the other. As noted previously, the problem is apparent in our daily phenomenological experience: Subjectively we experience that our conscious perception and cognition is constant, and that our representations of the external world evolve continuously (Taylor 2001). However, simultaneously, we are aware of a discrete sequence of cognitive events, where conscious percepts, mental images, and thoughts are separate "snapshots" of variable duration (Bickle et al. 2000). Evidently, this duality of subjective experience appears to be intrinsic to the principles by which cognition operates and therefore should be reflected in intrinsic neuronal mechanisms. However, many psychophysical and electrophysiological observations are interpreted theoretically either in a continuous or discrete manner, thus contributing to the well-known ("discreteness *vs.* continuity") dichotomy (for a detailed analysis, see Eliasmith 2000).

The ultimate purpose of the present article is to illustrate how discreteness and continuity could be theoretical "bedfellows." To our knowledge, no one has yet proposed a specific theory that utilizes at once both properties of "discreteness" and "continuity." This paper makes a first try. We suggest that the Operational Architectonics (OA) theory, which explores the temporal structure of information flow and the inter-area interactions within a network of functional neuronal assemblies by examining topographic sharp transition processes (on the millisecond scale) in the scalp EEG/MEG, may be a sufficient framework that would instantiate discrete conscious experiences without fundamentally violating the demand of continuity (primary references for OA theory are Fingelkurts and Fingelkurts 2001, 2003, 2004, 2005). However, to avoid any possible misunderstanding, we should stress that the goal of this paper is not to prove conclusively or to test the OA framework *per se*, but rather to show that it possesses sufficient levels of description and explanation to help account for temporal phenomena. The analysis in this paper extends the OA framework by developing an account of continuity-discreteness *unity* that has not previously been part of that or of other theories. It provides novel interpretations for continuity-discreteness phenomena, and most importantly, it makes testable predictions (see the last section).

We should stress, that in the present paper we will not address the works of Libet et al. (1979, 1983) and Dennett's Multiple Drafts Model (1991) or related studies and critiques (Gomes 2002; Velmans 2002; Revonsuo 1993; Korb 1993). Even though these are obviously related to the subject of timing in cognition, they are not directly relevant to the "discreteness *vs.* continuity" issue, which is the main topic of the present theoretical paper.

Below we first review briefly the arguments for discrete as well as for continuous properties/mechanisms of cognition. Then we explain the biological plausibility of EEG temporal dynamic structure (using the OA framework) for representing the dual temporal nature of cognition, and close by suggesting some interesting consequences of OA framework for cognition and consciousness.

2. Review of arguments

This section does not provide a thorough review of research, but rather it simply presents an overview of the main arguments (psychophysical, electrophysiological, and computational) in support of either discreteness or continuity. As it will be apparent, there are substantial theoretical disagreements of whether cognition and its neural representations occur in discrete epochs or continuously. Some have accepted the distinction, while others have argued that only discrete or only continuous processes can be studied experimentally, while still others have denied the conceptual distinction itself. The situation is complicated further by the fact that the terms used to define the "discrete" and "continuous" processes in the brain/mind differ across studies and researchers, and they have focused on different levels of description (e.g. the activity of individual neurons, the activity of neural assemblies, or large-scale activations). In the following sections, these terms are presented in the ways the cited authors have used them. The common for many arguments problem of conceptualization will be presented in the following third section.

2.1. Psychophysical support for discreteness in cognition

One of the earliest sources presenting consciousness as consisting of sequences of discrete events may be found in Buddhist texts, in which consciousness is described as a "momentary collection of mental phenomena" or as "distinct moments" (von Rospatt 1995). In modern psychology, the idea of discrete cognition and consciousness was firstly considered by William James (1890). However, it was quickly discarded and was seriously considered again only in the 20th century. One of the first pieces of empirical evidence came from "backward masking" or metacontrast research, which demonstrated that later sensory input could block perception of an earlier event (for an early overview see Alpern 1952; for a more recent review, see Bachmann 1994). Stroud (1955) was the first to start to use the notion of "*perceptual moment*", whereas earlier von Baer (1864) suggested the notion of a "*time quantum*" and important investigations in this vein have been further made by Geissler (1987, 1997; see also Vanagas 1994). Geissler formulated a taxonomic model of quantal timing (TQM), which is based on the entrainment of temporal intervals. In short, TQM imposes restrictions upon the sets of discrete intervals, which can alternatively be observed in a mental task (Geissler et al. 1999). Behavioral studies suggested that sensory systems integrate discrete temporal samples of incoming information in a sequential process, called the "*traveling moment of perception*"

(Allport 1968). Later, Efron (1970) suggested that conscious cognition is temporally discontinuous and parsed into sensory sampling intervals or "*perceptual frames*." These frames were estimated to be about 70-100 ms in average duration.

Many other psychophysical observations have been made about such discrete processes. For example, 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). This phenomenon was named *apparent simultaneity* and *temporal numerosity*[1], and it is compatible with the idea of a discrete perceptual "frame" of about 100 ms or less within which stimuli would be grouped and subjectively interpreted as a single event. Other findings concerned the *periodicity in reaction time* (Venables 1960; White and Harter 1969), the *periodicity in visual threshold* (Latour 1967) and the *perceived causality* (Shallice 1964). For a detail review of these psychophysical observations see the recent work of VanRullen and Koch (2003).

In his relatively recent work, Von der Malsburg (1999) has introduced the notion of the *"psychological moment,"* which is also compatible with the idea of discreteness. According to Malsburg, at times shorter than this moment, one can speak of a mental state or a brain state, whereas at times greater than this moment one sees a succession of states or a state history.

The experiments of Pöppel (1988, 1996, 1997) have also argued for the existence of a *temporal integration span* (TIS). This idea goes back to James's (1890) "*specious present*", and to early experiments on subjective grouping (see, for example Dietze 1885; Bolton 1894). Later, the concept of TIS was discussed by Fraisse (1978, 1984), Michon (1985), and Block (1990), who argued that the stream of consciousness is segmented in structurally unified portions.

In short, this brief review suggests that discrete conscious perception requires that two distinct events be judged as simultaneous or sequential depending on the time interval separating them (VanRullen and Koch 2003). Furthermore, perceptual moments or frames are controlled by a brain cortical mechanism that selects incoming information into discrete units of time by a gating process (Harter 1967). The arguments in favor of this suggestion will be elaborated in the following section.

---

[1] This means that there exists a particular minimal inter-stimulus interval for which two successive events are consistently perceived as simultaneous.

2.2. Electrophysiological support for discreteness in cognition

One piece of evidence supporting discreteness view is the fact that real neuronal networks form axo-dendritic synapses that are activated by action potentials, resulting in a discrete or *non*continuous release of neural transmitters, leading to a change in conductance and subsequent generation of synaptic current in the postsynaptic neurons (Poznanski 2002). Therefore, the rate of neural transmitter release is proportional to the individual spike activity arriving at the presynaptic terminals. Thus, it has been suggested that noncontinuous release of neural transmitters is probably responsible for the fact that the duration of long-lasting excitatory postsynaptic potential and inhibitory postsynaptic potential sequences present in mammalian brain neurons is normally in the range of 80-200 ms (Purpura 1972), which corresponds to the duration of “perceptual frames” (see the previous section). Sequential stimuli that occur within this *brief time interval* will be perceived as simultaneous, whereas events separated by a longer time are perceived as sequential. It has been suggested (see Flohr 1995) that the temporal extension of neural activity is critical for *perceptual binding*. In his extensive review, Harter (1967) listed a number of studies that supported the idea that individual neurons have an excitability cycle that determines their ability to respond to afferent signals. Indeed, when neurons in assemblies have synchronous excitability cycles, the transmission of afferent impulses through them could be gated by their excitability cycle (Harter 1967; Vartanyan et al. 1989; Hasty et al. 2001; Buzsáki and Draguhn 2004). Resent mathematical models (Izhikevich 1999; Giaquinta et al. 2000; Tonnelier 2005) confirm these findings.

Similar proposals come from electro- and magnetoencephalography (EEG/MEG) studies. A number of reports have suggested that EEG (and alpha rhythm in particular) is the basis of clock-controlling timing functions in the brain (for a review, see Surwillo 1966). Norbert Wiener (1961; the father of Cybernetics) ascribed the putative clocking mechanism in the brain to mutual entrainment of an ensemble of non-linear alpha generators. A strong proponent of the EEG as a base for a brain clock was Treisman, who proposed that both temporal perception and performance depended on EEG frequencies (Treisman 1963, 1984; Treisman et al. 1990, 1994). Of particular interest in this respect is the finding that the amplitude of the visual evoked potential depends on the phase of the background alpha rhythm when the flash stimulus is applied (Callaway and Layne 1964). Thus, Treisman stated that the overall pattern of EEG data might be interpreted as favoring a non-linear-pacemakers-controlling model for the organization of the brain’s temporal system. More recently, Shevelev et al. (1991, 2000) claim to have produced direct experimental support for the scanning hypothesis of perceptual framing. These authors found that when figure contours were relatively far from the fixation point, recognition was better during relatively earlier phases of the alpha wave (Shevelev et al. 1991). Also they found a relationship between the type of visual illusion and the direction that EEG waves travel (Shevelev et al. 2000). These results, as the authors state, indicate that EEG waves may be a reflection of the scanning process.

In recent years this kind of research has been extended. A number of researchers have argued that consciousness is *dis*continuous and is parsed into *sequential episodes* by means of synchronous thalamo-cortical oscillatory activity (Llinas and Ribary 1998; Edelman and Tononi 2000). Synchronized thalamo-cortical oscillations are considered to partly control the cortical rhythms, which may be associated with a gating mechanism that controls the "*chunking*" of perception (Gobet et al. 2001). Exactly cortical rhythms have been found to be closely related to temporal perceptual window (Varela et al. 1981; Gho and Varela 1988). Varela et al. (1981) showed a consistent correlation between the perception of apparent simultaneity and the alpha phase at which light stimuli were presented (see also Gho and Varela 1988).

To reconcile the evidence that conscious framing takes place simultaneously with the apparent continuity of perceptual experience, John (1990) proposed a mechanism, whereby a cascade of momentary perceptual frames converges on cortical areas to establish a steady-state perturbation (*spatiotemporal signature*) from baseline brain activity (John 2002). This mechanism has received substantial support from EEG studies, including research by Lehmann and colleagues (Lehmann 1971; Lehmann et al. 1987), which have demonstrated that the dynamics 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, these studies have shown that these microstates are associated with different modes of spontaneous thoughts (Koenig and Lehmann 1996) and with spontaneous visual imagery and abstract thoughts (Lehmann et al. 1998).

Recently more evidence accumulated suggesting that the apparently continuous stream of cognition and consciousness in fact consists of discrete units. It shows that there exist *subfields* of the brain, some of which are activated for only 20-50 ms during a presentation of stimuli, and that the combination of activated subfields varies even for a stationary presentation of stimuli (Tsuda 2001). It has been suggested that the dynamic of these fields may be a neural correlate of internal dynamics for restructuring and/or reorganization of mental space (Dinse 1990, 1994).

Bickle and colleagues (2000) suggested a *neurocomputational network* model that computes multiple-step sequences of cognition. According to this model a cognitive process is a sequential path through a vector from one (hyper-) point to another. The location of a (hyper-) point in the appropriate vector space represents the content of the state. Sequences computed in this way occur in an orderly fashion, moving sequentially from one unified representation or idea to another; the contents of later representations and steps in the sequence depend upon those of earlier representations and steps as well as on the later “target” states. For a relevant discussion of the neurobiological plausibility and limitations of this model, see Bickle et al. (2000).

Finally, very recent EEG studies have shown that the multi-variability of neuronal nets, reflected in EEG short-term spectral patterns, is evidently discrete in time and limited by the dynamics of the short *quasi-stable brain state*s (for the review of experimental evidence, see Fingelkurts et al. 2003).

In sum, the studies reviewed in this section support the idea of “perceptual frames” and provide the evidence for the neurophysiological mechanisms for such frames. However, as has been pointed by Churchland and Sejnowski (1992), the existence of *stable patterns* of activation at the neural level may simultaneously be consistent with the seamless nature of our ongoing phenomenal experience, since these stabilizations can occur very rapidly, thus leading to a *continuous* phenomenal stream (O’Brien and Opie 1999; for theoretical conceptualization, see Brown 1998).

2.3. Psychophysical support for continuity in cognition

In 1940 one of the principle architects of Gestalt psychology, Wolfang Köhler, proposed that the study of human conscious perception can leave no doubt that an adequate theory of perception must be a field theory. By this he meant that perceptual functions and processes are positioned on a seemingly continuous medium (Köhler 1940). Indeed, the subjective continuity of the present with the past is a major part of our everyday conscious experience. This perceptive presence is definable as a type of primary presentation in which objects are configured and detached from the background, and in which movement is perceived (Albertazzi 1998).

Another characteristic of the primary representation is that it is perceived as being in continuous change. Thus, according to Brown (1998) the most central aspect of a conscious state is the duration of a conscious moment, which is felt as a persistence over time. Brown observes, “We feel duration as a line in time, yet we are unaware that the perceptual contents within this duration are replicates that actualize over phases. The dynamic of individuation is obscured by its phenomenal products in the illusory stasis of the present. The duration of the present is felt but virtual, the duration of an entity, e.g., a mental state, is implicit yet real. The continuity of these durations – the present moment and the state that generates the present moment – is asymmetric since the former depends on the latter.” (Brown 1998, p. 239).

Birch (2002) extended this line of conceptualization by proposing that the operating modes of mentality are most likely continuous, rather than discrete. For example, sudden changes in a sequence of thoughts are not necessarily experienced as interruption. Consider the “watching a movie” metaphor, which is borrowed form Lehmann and colleagues (1998): While watching a movie, the viewer is exposed to disconnected bits and pieces over a period of two hours without even noticing any discontinuity, and builds a unified conscious percept. The evidence for continuous cognitive processes became even stronger with experiments, demonstrating that mental spatial transformations traverse the intermediate states of orientation, size, and location (Cooper 1975; Kosslyn 1975; Robins and Shepard 1977), and thus appear to be *analog/continuous*[2]. The mathematical definition of continuity of a line is that for any two points on the line, there is an intermediate point. Experimental data have suggested that the internal representation for the orientation of an object at a time between two discrete orientations is at an intermediate orientation (Cooper 1975; Robins and Shepard 1977). These data have been widely taken to support “analog” models of mental imagery. Generally, as suggested by Habel (1994), continuous representations seem to be necessary for an adequate dynamic representation of continuous processes and events such as motion. However, there are also events for which only the initial and the final points are relevant; in these cases, discrete dynamic representations seems to be more appropriate. For more information on analogue picture theories of mental imagery see the extensive review by Pylyshyn (2002).

Finke's (Finke and Kurtzman 1981) and Sheppard and Metzler (1971) experiments are often cited as proof that the phenomena of mental scanning use truly analog processes. For example, Birch (2002) suggests that holistically (non-propositionally) processed images might be irreducible elements in the computational processes performed by the brain and that the operating modes of imagery are continuous rather than discrete. He further states that imagist theorists have often used the term “analog” to designate processes that exhibit the smoothness

---

[2] Usually it is considered that things which are analog to be continuous and things which are digital to be discrete (Suber 1988; see also Eliasmith 2000). However, see Blachowitz (1997) in support of the ubiquity of this synonymizing and for an alternative to it.

or continuity in functionality that is thought, in their theory, to correspond to operations due to imagistic processes rather than due to discrete processes. A similar conceptualization may be found in Barsalou's (1999) relatively recent review, in which he states that perceptual symbols are dynamic, not discrete. His idea is that once a perceptual symbol is stored, it no longer functions rigidly as a discrete symbol.

Similarly, Hobson's (1992) *A*ctivation, *I*nput source and *M*odulation (AIM) model proposes that although specific states of consciousness can be meaningfully described, shifts in consciousness reflect movements through a continuously varying state space, and not discontinuous jumps between discrete states. According to this model, specific states become defined because normal subjects tend to remain in a highly constrained region of the state space for long periods of time and then rapidly move to another similarly constrained region (Hobson et al. 2000).

2.4. Neurophysiological and computational support for continuity in cognition

Another kind of support for the continuous nature of cognition came from neurophysiological research. Classical theories of intracellular potentials propose that there exists a standing gradient – a continuous current – between dendritic and axonal poles of neurons (Bullock 1997). Intercellular interactions can also be described in terms of a continuum, meaning that a *continuous function* may be derived by appropriate transformations to describe the active state of the whole set of neurons (Freeman 1972). The theoretical roots of this so called dynamicism are derived from the mathematical theory known as "dynamical systems theory," which uses sets of differential equations to describe the evolution of a system through time (Eliasmith 2001).

Central/cortical neurons, unlike the peripheral neurons, have continual background activity, owing to synaptic interactions with their neighbors. Each pulse exerts an excitatory action that is returned in a randomized distribution over time by innumerable other neurons at differing distances and conduction delays, which can be modeled as a diffusion process (Freeman 1974). Due to the large number of neurons in each local neighborhood, the density is *continuous* and not discrete. It is a macroscopic variable, like the local temperature of a gas (Freeman and Barrie 1993), which may be responsible for conscious perception (see also Wright et al. 2001). This "collective" parameter, which aggregates the behavior of many neurons, is treated as "completely" continuous (van Gelder 1995) since "there is no possibility of nonarbitrarily dividing its changes over time into distinct manipulatings, and no point in trying to do so" (van Gelder 1995, p. 354).

A distinct line of argument lies in the Shannon's (1948/1949) information processing theory. According to this framework and as has been later proposed by Eliasmith (2000), if the exact arrival times of neuron spikes are important then we need a real number to express those arrival times. However, real numbers can only be expressed by an infinite bit string, so each spike carries with it an infinite amount of information. In this case, it is clear that the brain is continuous in its fine details, that is, relative to sub-microsecond time steps. However, if exact arrival times are not important then there is reason to believe that the brain is not continuous, but rather discrete relative to millisecond time steps (see extensive analysis and discussion in Eliasmith 2000). In general, many researchers studying mental imagery believe that mental images are analog representations (Jeannerod 1994) and are "far too metaphorical and analog in principle to fit easily into [a] kind of quasi-symbolic computational framework" (Donald 1993, p. 740).

Suggestions have been put forward to describe how perceptual symbols may have a continual dynamic (Barsalou 1999). Since a perceptual symbol is viewed as an associative pattern of neuronal activity, its subsequent activation has dynamic properties. Subsequent storage of additional perceptual symbols in the same association area may alter connections in the original pattern, causing subsequent activations to differ. Thus, different contexts may distort activations of the original neuronal pattern, as connections from contextual features bias activation towards some features in this pattern more than others. In these respects, a perceptual symbol may be seen as an attractor in a connectionist network. As the network changes over time, the attractor also changes, and as the context varies, activation of the attractor co-varies. Thus, a perceptual symbol is neither rigid nor discrete, but continuous (Barsalou 1999).

This section has presented only selective electrophysiological and computational arguments in support of the continuous nature of cognition. Collectively these considerations suggest that even if there are transitions between states, if the similarity between alternative neighboring states and trajectories is emphasized, then the dynamical system is seen as a close approximation to a continuous, analog, law-like physical process (Cariani 1997; for a theoretical conceptualization, see Brown 1998).

3. The problem of conceptualization

The previous four sub-sections have shown that both discrete and continuous explanations for cognition and brain functioning are legitimate. Each offers some insight regarding temporal phenomena displayed by cognitive systems. However, neither the discrete nor continuous explanation, by itself, simultaneously takes into account both temporal aspects, as they are unified in cognition and in subjective experience. Therefore, we argue that neither description, in isolation, is satisfactory. It seems that at least a part of the problem is based on wrongly chosen levels of description and explanation. If the discrete or continuous nature of brain processes on the particular level of brain organization does not affect the cognitive behavior of the system (brain) then we should not consider such level of description. We believe that the appropriate level should articulate the *phenomenal level* of brain organization, and in particular, of cognition and consciousness (as suggested by Revonsuo 2001).

As it is apparent from the previous section, the problem of conceptualization arises when some researchers attempt, on the one hand, to relate the discrete events (discharges of neurons) to the subjective experience of continuity and, on the other hand, try to explain through the continuous in time and space electrical brain field the sequence of discrete thoughts and mental states. In such attempts, it is implicitly or explicitly assumed that *discreteness* presupposes periods of "work" and "silence," thus implementing the *gaps* in the process, whereas for the *continuity* presupposes that time and space are continuous and do not contain gaps. Furthermore, according to the discrete model (Sternberg 1969), there is no temporal overlap among various cognitive processes; rather, they occur in a strict sequence, where each process (stage) starts only after the immediately prior one has finished. Continuous models, in contrast, assume that information is transmitted between component mental processes in a gradual fashion and can be described by a continuous mathematical function (see Meyer et al. 1985). It is also supposed that representations undergo continuous change in relation to changes in the external environment. We do not agree with these views for several reasons.

First, as stressed by Noë and Thompson (2004), the fact that we have a continuous experience does not necessarily imply that the pattern of neural activity responsible for that experience must itself be continuous. As was shown by Meyer et al. (1985), discrete processes can, with selected conditions, mimic the properties of continuous processes. Secondly, for most physical (and neural) systems, as has been conclusively shown by Eliasmith (2001), the continuous nature of their processes is irrelevant for characterizing their information processing, which may very well be discrete[3]. That is why, thirdly, the *transition* (sudden jump) between states *per se* is not a gap, rather it is a continuous process (in time) from one state/representation to another (Fig. 1A)[4]; it is only the rapid speed of the transition (approximated as a time point) relative to the time spent in each "state" that makes transition appear as a *rapid shift* (Fingelkurts and Fingelkurts 2001). A time point is a mathematical construct analogous to a point in Euclidean geometry (strictly speaking, it has no duration), whereas a time span (duration) or interval is analogous to a line segment (Rensing et al. 2001). In this context, the width of excitatory or inhibitory postsynaptic potentials (EPSP/IPSP) could vary in a continuous manner (even though it is finite). Thus, EPSP/IPSP intervals, as well as their sum within intervals of coherent activity of whole neural assemblies, may be seen as analog codes (Cariani 1997). This makes them suitable for "bridging" the continuous and discrete brain processes which subserve cognition and subjective experience (Fingelkurts and Fingelkurts 2003).

Each of the descriptions of brain temporal mechanisms (mentioned in the second section) that underlie cognition and consciousness has usually been tackled by the researchers separately, not simultaneously. This is inherently implausible and requires significant over-simplification. However, the understanding of the concepts "continuity" and "discreteness" in their *unity* (not just as a mixture of analog and digital processes; Uhr 1994) is of scientific importance for cognitive neuroscience. In this respect, at what level can brain processes be described which would instantiate discrete conscious experiences without fundamentally violating the demand for continuity?

4. EEG dynamics

Recent work in different fields of cognitive neuroscience seems to support the idea that the "translation" from phenomenological/psychological constructs to brain activity should focus on the dynamic operations of *large-scale cortical networks* (see Edelman and Tononi 2000;

---

[3] Consider a typical transistor. The processes in it are indeed continuous: That is its transfer function traces out a (nonlinear, continuous) S-shaped curve, - that is why they are used as both switches and amplifiers (Eliasmith 2002). Nevertheless, we treat them as if they are only ever in one of the two possible states. Consistently with this analogy, van Gelder (1995) claims that even though neurons and neuronal assemblies may be considered as discrete in state, this does not mean that they are discrete in time.

[4] Figure 1 also illustrates the continuity and discreteness for the spatial dimension (see B). For the case of continuity, the change of neuronal activity appeared in a gradual fashion, whereas for the discrete condition, the change of neuronal activity appeared abruptly.

Bressler and Kelso 2001; McIntosh et al. 2001; Revonsuo 2001; Varela et al. 2001; John 2002). These neural networks are considered to be functional, meaning that the units in such networks

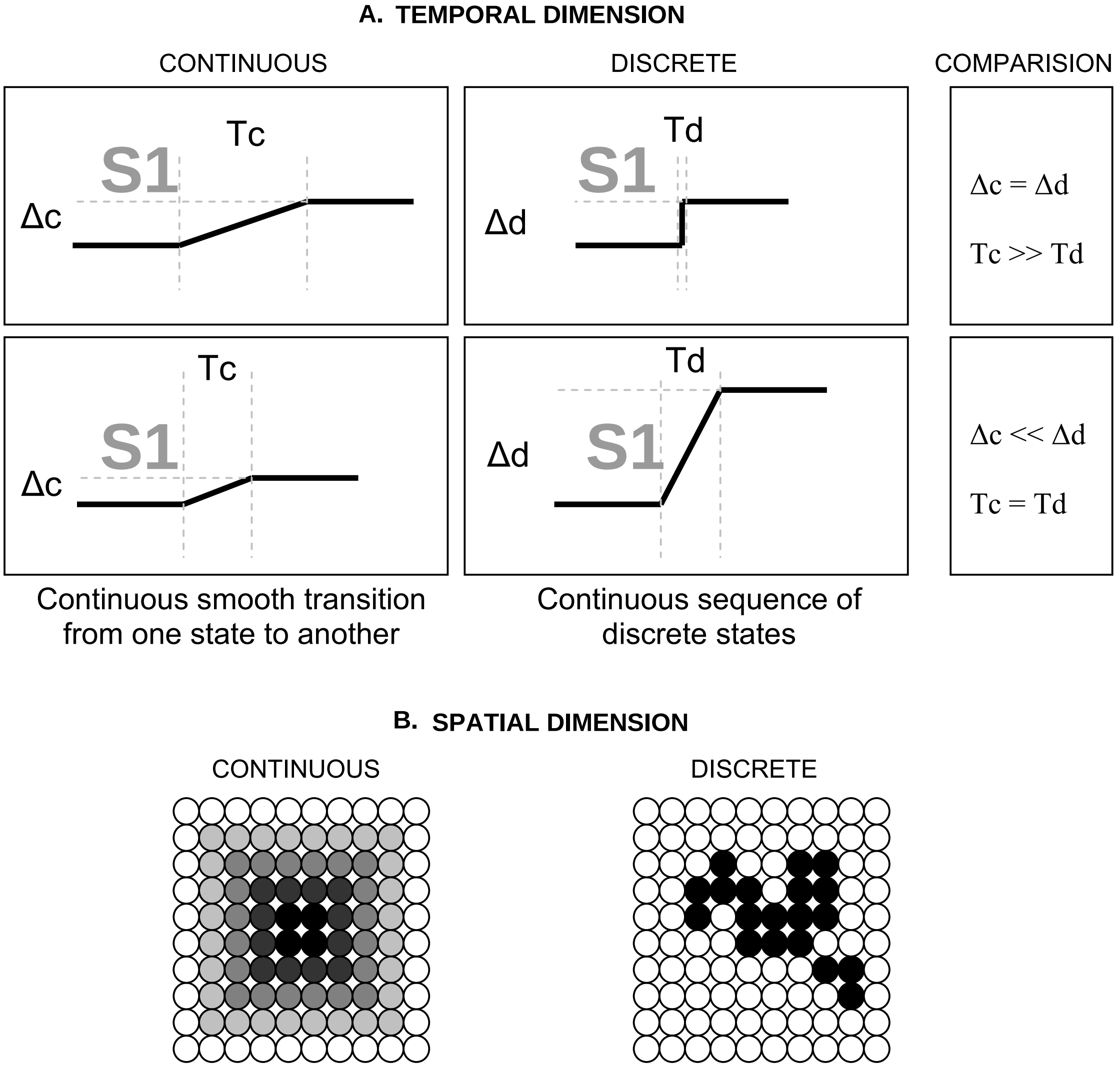

Figure 1. Schematic illustration of continuous and discrete change of brain states. *A*, Temporal dimension. Lets observe an example, when the amplitude shift between two states is constant (Δc = Δd), then the case of a long enough transition period between these two states would be conditional for a continuous change. In contrast, when the transition period is extremely short relatively to the stabilized period, the abrupt (discrete) change between two states has to be present. Thus, Tc >> Td. Now lets consider the situation when the amplitude shift between two states is larger in one case than in the other (Δc << Δd). In this example, in case of small amplitude shift, relatively short transitive period would signify the smooth continuous change from one state to another. The same transitive period (Tc = Td) in case of a large amplitude shift (relatively to the stabilized period) between two states would mean abrupt change (jump). *B*, Spatial dimension. Gradation of color represents continuous or abrupt changes of states. *Tc*, transition period (continuous); *Td*, transition period (discrete); *Δc*,

amplitude shift (continuous); *Δd*, amplitude shift (discrete); *S1* and *S2*, first and second brain states.

are the transient neuronal assemblies, which can quickly become associated or disassociated (Triesch and von der Malsburg 2001; Bressler 2003). The EEG is the correct measure to study the behavior of large-scale networks, because it is a highly organized macro-level electrophysiological phenomenon in the brain, which captures the operations of large-scale cortical networks and which is remarkably correlated with both behavior and cognition[5] (Kaplan and Shishkin 2000; Nunez 2000; John 2001; Freeman 2003; see also recent detailed review Fingelkurts and Fingelkurts 2005). Behavior and cognition in their turn has been supposed to be reflected in the *temporal structure* of EEG (see reviews Fingelkurts and Fingelkurts 2004; Kaplan et al. 2005). In this respect, the dynamic and temporal structure of EEG field – in other words, its *non*stationarity (Kaplan 1998; Fingelkurts and Fingelkurts 2001; Kaplan et al. 2005) – deserves wider coverage and more systematic research. The understanding of the nonstationary structure of EEG signal is of intrinsic scientific importance, because without understanding the character of the EEG processes under consideration, the use of many methods for EEG analysis gives often false results. Despite a large body of interesting and important EEG findings (Edelman and Tononi 2000; Nunez 2000; Bressler and Kelso 2001; Varela et al. 2001; John 2001; Freeman 2003), the experimental verification of the dynamical and temporal phenomena in the EEG meets with serious methodological difficulties, which are mainly due to contemporary paradigms of experimental measurement and EEG analysis. For example, invariants such as the mean power/amplitude spectrum, average ERP and ERD/ERS, coherency, fractal dimensions, Lyapunov exponents, and others have an interpretation only for stationary dynamics (Landa et al. 2000). Further, the nonstationarity of the EEG process usually does not allow researchers to construct a global dynamical model for the whole observable phenomenon (Skinner and Molnar 2000). Thus, regardless of how

---

[5] To illustrate this point, consider only one example, which we borrow form Llinas et al. (1998, p. 1841): “We know full well that if we are tired we can fall asleep extraordinarily quickly and that if we are asleep and a strong stimulus is given to us (e.g. the havoc played by an alarm clock) we can awaken also extraordinarily fast. It is so fast, indeed, that the only substrate capable of supporting the speed of these two events must be electrical in nature given the large number of elements involved…” EEG is mainly the “product” of the cortex. With this respect, there is interesting finding: Sahraie et al. (1997) compared brain activity in a single blindsight subject (G.Y.) generated by stimuli which give rise to awareness with activity generated by stimuli (permitting similar levels of discrimination) without awareness. They found that the shift between “aware” and “unaware” modes was associated with a shift in the pattern of activity from cortical to subcortical levels. Nunez (2000) also stated that subcortical activity is only weakly correlated with cognition and behavior. However, one should acknowledge the importance of such factors as the effects of some definite neurotransmitters controlled by thalamus (Newman 1995) and the establishment of reentrant thalamocortical loops for oscillatory EEG synchronization in order to bind specific features for consciously cognitive representation of the objects that are integrated from these features (Bachmann 1984; Llinas et al. 2002).

powerful or statistically significant the different estimations of averaged EEG phenomena may be, difficulties remain in their meaningful interpretation if they are not matched to their piecewise stationary structure (Effern et al. 2000; Laskaris and Ioannides 2001; Fingelkurts et al. 2002). Stated simply, the nonstationary nature of EEG field can be tested only by adequate procedures, sensitive to this nonstationarity.

Despite methodological limitations, there has recently been a shift towards explaining cognitive functions in terms of the joint behavior of large neuronal populations that are dynamically bound together (von der Malsburg 1981; Gray and Singer 1989; Varela et al. 2001; Revonsuo 2001). Several experimental studies have suggested that a crucial feature of most cognitive functions is a considerable potential multivariability of neuronal networks, which can simultaneously integrate and segregate the activities of multiple distributed cortical areas (Edelman and Tononi 2000; for the recent review, see Fingelkurts and Fingelkurts 2004). Within this framework, the dichotomy between "discreteness and continuity" – as well as between "associationism (Hill 1991; Watson 2003) *vs.* structuralism (Fodor and Pylyshyn 1988; Chomsky 1957)" and "localizationism (Zeki 2003) *vs.* globalism (Luria 1980)" – becomes irrelevant, as both ends of the dichotomy can be embodied and observed in the moment-by-moment states of this large-scale network of neural populations (Bressler 1995; Pascual-Marqui et al. 1995; McIntosh et al. 2001). *Operational Architectonics* (OA) framework of brain functioning[6] extends and develops this point of view (Fingelkurts and Fingelkurts 2001; for generalization, see also Fingelkurts and Fingelkurts 2005). In contrast to other theories, the OA framework explicitly incorporates the nonstationary nature of electromagnetic brain field.

4.1. Operational Architectonics of EEG brain dynamic

In this paper, for sake of shortness, we will only very briefly summarize the main points of OA framework. We assume that the level of organization at which mental states and cognition (in particular phenomenal consciousness) reside might be the highly organized macro-level electrophysiological phenomena (*metastable operational modules*) in the brain, which are realized by the coordinated electrical activity (*operational synchrony*) of many neuronal populations dispersed throughout the brain (Fingelkurts and Fingelkurts 2001, 2003). The

---

[6] The OA framework has its origin in the work of Kaplan and coworkers (Kaplan 1995, 1998, 1999; Kaplan et al. 1997; Kaplan and Shishkin 2000). We thoroughly endorse what they state, since our own particular perspective on the problem of brain-mind functioning does not differ substantially, although our choice of emphasis is very different in places.

activity of these neuronal populations is "hidden" in the complex nonstationary structure of biopotential brain field – i.e., EEG (for the reviews, see Fingelkurts and Fingelkurts 2004, 2005). The OA theoretical framework has some similarities with other relevant related theoretical frameworks (see Appendix A for details).

In the OA framework, the neuronal populations (or assemblies)[7] are thought to underlie the elemental operations of cognition or behavior (Damasio 1994; von der Malsburg 1999; Varela et al. 2001; Fingelkurts and Fingelkurts 2003; Crick and Koch 2003). Studies over three decades lead to the suggestion that individual elements of information are encoded not by single cells, but rather by populations of cells (Tononi and Edelman 1998; Pouget et al. 2000). 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 eventually consciousness (Singer 2001). Therefore, the activity of any individual cell is informative only insofar as it contributes to the *overall statistics of the population* of which it is a member (John 2002). It is the set of emergent properties of many abundant elements in the assembly that is important, whereas the global features (or order parameters, Haken 1996) constrain the activity of each neuron. In this sense, the representation of information by neuronal populations is *ergodic* (analogous to the generation of pressure by water molecules in an enclosed volume, John 2001). Therefore, the representation of information by neuronal populations is *robust*, meaning that damage to (or the death of) a single cell will not have a catastrophic effect on the representation of information. Additionally, neuronal populations have other key properties, such as mechanisms for noise removal, short-term memory, and the instantiation of complex, nonlinear functions (see Pouget et al. 2000).

It has been shown that neuronal assemblies have a transient dynamical existence (i.e. a functional life-span), which means that their correlated activity persists over substantial time intervals (Pelliomisz and Linas 1985; Makarenko et al. 1997; for the review, see Nunez 2000). The fact that neurons are able to synchronize their subthreshold oscillations (EPSPs/IPSPs), leading to fixed states of an overall neuronal assembly and to rapid transitions between such

---

[7] This approach goes back to Hebb (1949); however, the classical neural assemblies are too slow and may be not suitable for cognitive operations (Kaplan and Borisov 2003). Modern understanding of neural assemblies stresses its functional nature, which is at scales both coarser and finer than that of the classical ones (von der Malsburg 1999). The idea is that large neuronal populations can quickly become associated or disassociated, thus giving rise to transient assemblies (Frison 2000; Triesch and von der Malsburg 2001), which thought to execute the basic operations of informational processing (Averbeck and Lee 2004). For definition of "brain operation," see Fingelkurts and Fingelkurts (2003, 2005). It is important to note here that the cell assembly's concept is difficult to falsify (see Appendix B for details).

states, has been shown experimentally and in computational models (Makarenko and Llinas 1998). Generally, the overall pattern of neuronal assembly's correlated activity is very sensitive to fluctuations and it may be swiftly rearranged during rapid shifts (Kirillov and Makarenko 1991; for review, see Singer et al. 1997). As has been demonstrated *in vitro*, these intervals of correlated activity are manifested in the oscillatory waves, which are the result of neuronal clustering (Leznik et al. 2002). Thus, at the EEG level these intervals should be reflected in defined periods (segments) of *quasi-stationary activity*[8] operating in different frequency ranges (for reviews, see Fingelkurts and Fingelkurts 2001, 2003, 2005; Kaplan et al. 2005). Yet in 1972 year, it was experimentally shown in detail by Elul, that EEG is a product of (de)synchronized neurons within cellular assemblies (Elul 1972a,b). Indeed, EEG waves recorded from the scalp are integrated EPSPs and IPSPs 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" or a "wave packet," Freeman and Vitiello 2005) in the neuronal masses near to the recording electrode. Even though the cells that comprise an assembly under the electrode may be spatially intermixed with cells in other neuronal assemblies performing different computational tasks, they would be separated by different time-scale coherence (EEG frequencies and amplitude variability; Basar 2005). In this case, it is possible to consider one EEG segment as the single event in EEG-phenomenology. Within the duration of one such segment, the neuronal assembly that generates the oscillations is in the steady quasi-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 coherent sub-systems (Jansen et al. 1988; Kaplan and Shishkin 2000; Freeman and Vitiello 2005).

The segments of quasi-stationarity can be obtained using an adaptive segmentation approach (Kaplan et al. 2005; see also Brodsky et al. 1999; Fell et al. 2000; Kaplan and Shishkin 2000). The aim of the segmentation procedure is to divide the EEG-signal into quasi-stationary segments by estimating the intrinsic points of "gluing" (in mathematical statistics this problem is known as the "change-point problem"; see Brodsky and Darkhovsky 1993). These instants (the transient phenomena) within short-time window when EEG amplitude significantly changed were identified as *rapid transition processes* (RTP) (Kaplan et al. 1997; Fingelkurts and Fingelkurts 2001). RTP is supposed to be of minor length comparing to the quasi-

---

[8] If the data is stationary, its dynamics does not change significantly during the acquisition period, thus been stable. Therefore, quasi-stationary means almost (or near) stable.

stationary segments, and therefore can be treated as a point or near-point (Fingelkurts and Fingelkurts 2001). 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). The RTPs or jumps in EEG amplitude are, in fact, the markers of boundaries between concatenated quasi-stationary segments (Fig. 2). An adaptive segmentation approach permits estimation of several characteristics (attributes) of the obtained EEG segments (Kaplan and Borisov 2003). These attributes[9] reflect different aspects of local processes in the cortex (Fig. 2) and thus permit the assessment of the mesolevel description of cortex interactions (interactions within transient neuronal assemblies) through large-scale EEG estimates (see Fingelkurts et al. 2004b, for experimental support and detailed discussion).

It has been shown experimentally that the sequences of segments between different EEG channels are to a certain extent synchronized, forming short-term *metastable*[10] topological combinations or *operational modules* (OM)[11], with different size (number of cortical areas involved) and life-span (Fingelkurts 1998; Kaplan and Shishkin 2000; Fingelkurts et al. 2003a,b). The notion of operational space-time applies here. Intuitively, the *Operational Space-*

---

[9] The attributes are the following: (1) Average amplitude within each segment (μV) – as generally agreed, indicates mainly the volume or size of neuronal population: indeed, the more neurons recruited into assembly through local synchronization of their activity, the higher will be the amplitude of corresponding to this assembly oscillations in the EEG (Nunez 2000); (2) Average length of segments (ms) – illustrates the functional life-span of neuronal population or the duration of operations produced by this population: since the transient neuronal assembly functions during a particular time interval, this period is reflected in EEG as a stabilized interval of quasi-stationary activity (Fell et al. 2000; Kaplan and Shishkin 2000); (3) Coefficient of amplitude variability within segments (%) – shows the stability of local neuronal synchronization within neuronal population or assembly (Truccolo et al. 2002); (4) Average amplitude relation among adjacent segments (%) – indicates the neuronal assembly behavior – growth (recruiting of new neurons) or distraction (functional elimination of neurons) (Kaplan and Borisov 2003); (5) Average steepness among adjacent segments (estimated in the close area of RTP) (%) – reflects the speed of neuronal population growth or distraction (Kaplan and Borisov 2003).

[10] Although the concept of metastability has been around in physics for a long time, the specific interpretation of metastability in the context of a theoretical model of the coordination dynamics in the brain has been developed by Kelso (1991). Metastability is a theory of how global integrative and local segregative tendencies in the brain coexist (Kelso 1995; Friston 1997; Kaplan 1998). In the metastable regime of brain functioning, the individual parts of the brain exhibit tendencies to function autonomously at the same time as they exhibit tendencies for coordinated activity (Bressler and Kelso 2001; see also Fingelkurts and Fingelkurts 2001, 2004). The synchronized operations of distributed neuronal assemblies are metastable spatial-temporal patterns because intrinsic differences in activity between the neuronal assemblies are sufficiently large that they do their own job, while still retaining a tendency to be coordinated together.

[11] 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 synchro-complexes (SC). Whereby, SC is a set of EEG channels in which each channel forms a paired combination (with high values of index of structural synchrony) with all other EEG channels in the same set (Fig. 3A); meaning that all pairs of channels in an SC have to have significant index of structural synchrony (Fingelkurts et al. 2004b). For the properties of OM see Fingelkurts and Fingelkurts (2005).

Time (OST) is the abstract space and time “constructed” by the brain each time a particular OM emerges. Formally, the OST concept holds 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) comprises 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

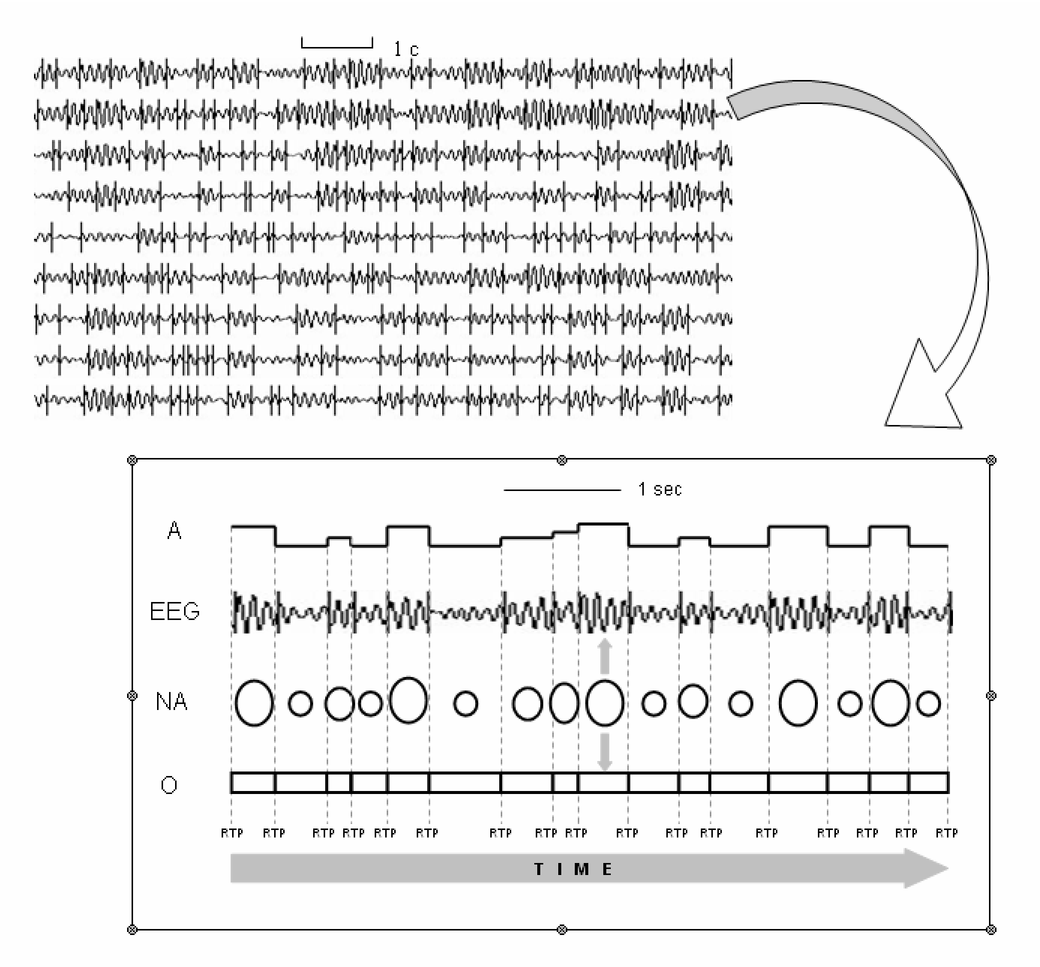

Figure 2. Correspondence between neuronal assemblies and EEG segments. At the top of the figure nine EEG channels filtered in the alpha frequency band (7-13 Hz) are presented. At the bottom of the figure right occipital EEG channel is presented with corresponding characteristics. *A*, Average amplitude of EEG segments across time-period *t*; *EEG*, Electroencephalogram; *NA*, Neuronal assemblies of different size; *O*, Operations of different duration; *RTP*, Rapid transition periods (boundaries between quasi-stationary EEG segments).

the same space-time of the same OM (although they may relate to some other OM). The sketch of this general idea is presented in the figure 3.

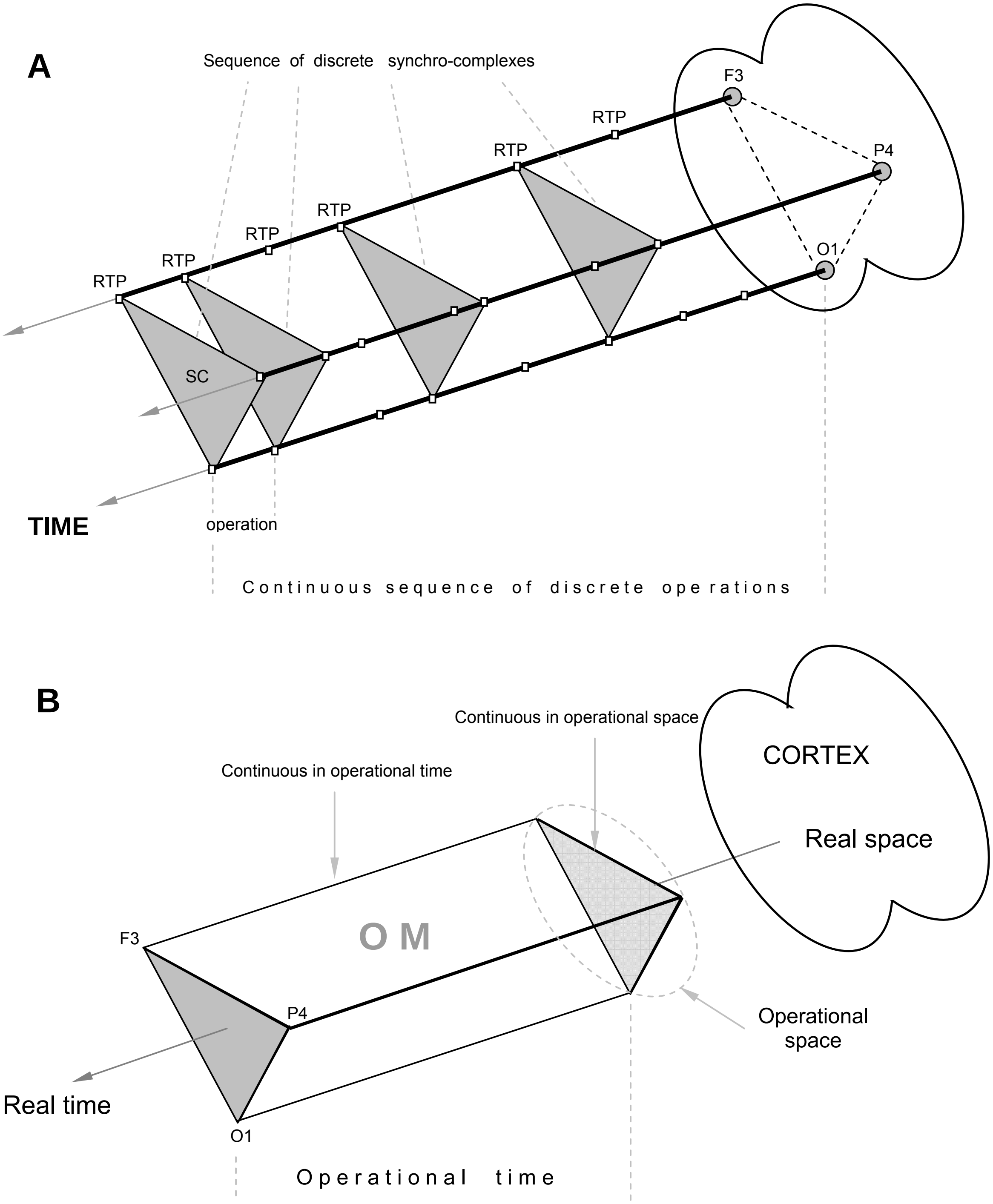

Figure 3. Operational module (OM) and operational space-time (OST). Each OM exists in the OST, which is "blind" to other possible time and space scales present simultaneously in the brain system. In the other words, all neural assemblies that do not contribute to a particular OM are temporarily and spatially excluded from the OST. *A*, Technical estimation of OM; *B*, Illustration of OST. Explanations are done in the text. *RTP*, Rapid transition periods

(boundaries between quasi-stationary EEG segments); *SC*, Momentary synchro-complexes (synchronization of RTPs between different local EEGs at the particular time instants); F_3, The left frontal area; P_4, The right parietal area; O_1, The left occipital area. As an example, only neural assemblies in these areas (operational space) synchronize their operations on a particular (operational) time-scale.

A quantitative description (Kaplan et al. 2005) of this type of synchrony, also called *structural synchrony* (SS)[12], provides the means for a radically new insight into the co-operation of the brain's systems, and it offers a mechanism of how discrete brain operations are bound together into a unified complex cognitive operation/function (Fingelkurts and Fingelkurts 2003; Fingelkurts et al. 2005). Thus, the structural (or operational) synchrony measure enables researchers to detect periods with a more or less generalized stabilization (*metastable OMs*) in the dynamics of the spatial mosaic of segments of the brain electromagnetic field (Fingelkurts and Fingelkurts 2001, 2003). It was demonstrated experimentally that the OMs *transition* appears *abruptly,* when the set of brain areas which constitute an OM rapidly looses functional couplings with each other and establishes new couplings within another set of brain areas, thus demarcating a new OM in the space-time continuum, Fig. 4 (Fingelkurts 1998; Fingelkurts et al. 2003b; see also John 2002 for the possible mechanism; and Brown 1998 for a philosophical conceptualization). These distinctive jumps between OMs have the appearance of a spatio-temporal *dis*continuity revealed in the EEG global field (which is not to be confused with abrupt jumps in the local EEG fields – concatenated quasi-stationary segments). Therefore, the apparent EEG field discontinuity was adopted as the sign of a state transition in cortical (and subcortical) dynamics (Fingelkurts and Fingelkurts 2001; for similar ideas see also Bressler 1995; Freeman 2003; Freeman and Vitiello 2005). First substantial experimental support for this formulation was obtained within the framework of the brain microstates concept: Momentary cortical electric field distributions are abruptly upgraded and replaced constantly (Lehmann 1971; Lehmann et al. 1987), and are associated with "atoms of thought" (Lehmann and Koenig 1997; Lehmann et al. 1998). Later it has also been shown experimentally that the metastable topological combinations in the EEG field appeared to be correlated with and dependent on individual levels of anxiety (Shishkin et al. 1998), cognitive tasks (Fingelkurts et al. 2003b), multisensory perception (Fingelkurts et al. 2003a), pharmacological influences (Fingelkurts et al. 2004a,b), large ontogeny shifts (e.g.,

---

[12] The index of structural synchrony (ISS) is estimated through synchronization of rapid transition processes (RTP) – boundaries between quasi-stationary segments – between different EEG channels. This procedure reveals the functional (operational) interrelationships between cortical sites as distinct from those measured using correlation, coherence and phase analysis (Kaplan et al. 2005).

between children and adults) (Borisov 2002), and changes in the functional state of brain during schizoid diseases (Kaplan and Borisov 2002).

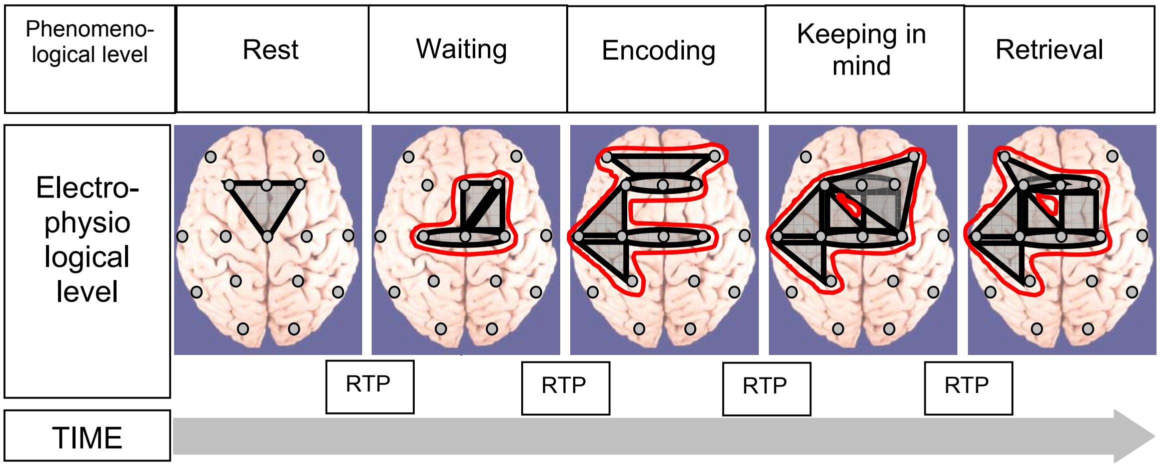

Figure 4. Isomorphism between functional structures of phenomenological experience and electromagnetic brain field. Phenomenological level illustrates the ever-changing stream of cognitive acts (in limit, thoughts or images) where each momentarily stable pattern is a particular cognitive macro-operation. Thus, stream of phenomenal experience has a composite structure: It contains stable nuclei (or cognitive operations/thoughts/images) and transitive fringes or rapid transitional periods (RTP). 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. Grey out-lined shapes illustrate complex OMs. Changes from one cognitive act to another are achieved through RTPs. Experimental data are represented from the original study by Fingelkurts et al. 2003b.

The mean duration of OMs (for a native EEG with a frequency band of 0.3-30 Hz) usually varies from 80-100 ms (for OMs which cover large part or entire cortex)[13] to 30 sec (for small OMs). These accounts, including variations in duration, are consistent with known estimates of cognitive processes, and of “moments of experience” or “thoughts”, which may vary between tenth of milliseconds and several seconds depending on circumstances (Pöppel 1988). However, it was shown that some OMs for specific brain oscillations are very stable and do not change across multistage experimental conditions (Fingelkurts 1998; Fingelkurts et al. 2003b). These stable OMs are probably responsible for long-lasting, complex brain operations and body “housekeeping” tasks. Considering the polyphonic character (mixture of different frequency oscillations) of the EEG field (Nunez 1995; Basar et al. 2001; Basar 2004) and the hierarchical nature (different time-scales) of segmental descriptions of local EEG fields (Kaplan 1998;

---

[13] These values coincide precisely with the mean microstate duration of entire neocortex (82 ± 4 ms) obtained for healthy young adults using Lehmann approach (Koenig et al. 2002), which is essentially different from our method. Thus, these data cross-validate each other.

Kaplan and Shishkin 2000), OMs could coexist on different time-scales, over spatial patches ranging from a small number of brain areas to an entire hemisphere and eventually, the whole brain (Fingelkurts and Fingelkurts, 2003; for the experimental support see Fingelkurts 1998; Fingelkurts et al. 2004b). Thus, microstate transitions (which illuminate sequences of concatenated quasi-stationary segments) may occur continually and locally in every area of the cortex (yielding parallel processing), leading to superimposed spatio-temporal patterns of stabilized activity (indexed as OMs) with fractal distributions of size and duration[14] (for similar formulation, see Freeman 2003). In this way, OMs lie, in some sense, between classical and connectionist architectures. They resemble connectionist networks (Churchland and Sejnowski 1992) in many respects: They may serve as associative, content addressable memories, and they are distributed across many neural assemblies. Yet, the specific temporal patterns (OMs) by themselves are unitary, like symbols of classical logics (Fodor and Pylyshyn 1988).

Thus, *discreteness* of parallel brain operations (indexed as sequences of concatenated quasi-stationary segments in local EEGs) is implemented in the *continuity* of unified metastable spatio-temporal patterns (indexed as OMs) of brain activity (Fig. 3). In other words, the continuity of OMs exists as long as the set of brain areas keeps synchronicity between their discrete operations. We argue that at the phenomenological level, a continuity of consciousness would be experienced. This conclusion is consistent with the view presented by Damasio (2000) that consciousness comes from the abundant flow of endless narratives of the processed objects and their features in different brain areas.

The statistical properties described above characterize a system that can maintain itself in a state of self-organized criticality (Bak et al. 1987; Barrie et al. 1996; Linkenkaer-Hansen et al. 2001; Freeman et al. 2000; Hwa and Ferree 2002). Thus, in the framework of the *Operational Architectonics (OA)* theory of brain functioning, the brain can be regarded as a massively interactive organ, without centralized control, that maintains itself in *metastable states* that combine *long-term continuity* with the capacity for rapid change (marks of *discrete* events) in accord with sudden and unpredictable changes in environments, both inside and outside the body (Fig. 4; Fingelkurts and Fingelkurts 2004, 2005; see also Freeman 2003, Freeman and Vitiello 2005 for similar conceptualization). In such a way, the OA framework suggests the

---

[14] It has been demonstrated that if two areas of cortex are operationally synchronized, then they tend to be also synchronized with some other areas (Fingelkurts 1998). Calculations showed that the power-law statistics governs the probability that a number of cortical areas are recruited into an OM. This ubiquitous dependency is characterized by a fractal relation between different levels of resolution of the data, a property also called self-organized criticality (Bak et al. 1987).

natural principle which may underlie and unify in a plausible manner the dual nature (*discreteness* and *continuity*) of cognition and consciousness.

5. Implication of Operational Architectonics framework for cognition and consciousness

According to the OA framework, both *discreteness* and *continuity* appear to be intrinsic to the neurophysiological principles by which the brain operates, and they are highly and naturally entangled through self-organized *operational synchrony* (OS) processes among neurons within a local region, as well as between many regions. It is tempting to believe that electromagnetic brain field complexity is mirrored in phenomenological (functional) complexity and vice versa. Thus, it has been suggested, based on the principle of functional isomorphism[15], that the large-scale spatial EEG mosaic of metastable operational modules (OM) may underlie mental states and conscious states, in particular (see Fingelkurts and Fingelkurts 2001, 2003 for a detail discussion). The main idea is that the structure of the electrical brain field, the structure of cognition, and the phenomenal structure of consciousness, all have the same organization (Fig. 4): The succession of discrete and relatively stable periods (metastable OMs, cognitive acts or thoughts, correspondingly) separated by rapid transitive processes (abrupt changes between OMs, cognitive acts or thoughts, correspondingly) (Fingelkurts and Fingelkurts 2001)[16].

More specifically, feature extracting neural assemblies, which are dispersed throughout the brain, decompose in parallel the complex stimulus into so-called *fragments of sensation* (John 2002). For example, for the visual modality (being the best investigated), selective neural activity for each dimension of the stimuli has been discovered in distinct and topographically organized areas of the visual system in rats, cats and primates, including humans (for review, see Lennie 1998). Summarized fluctuations of post-synaptic excitatory and inhibitory membrane potentials (EPSPs/IPSPs) in these neural assemblies become non-random, reflected in a concatenation of quasi-stationary intervals/*segments* at the local EEGs (Fingelkurts and

---

[15] Isomorphism is generally defined as a mapping of one entity into another having the same elemental structure, whereby the behaviors of the two entities are identically describable (Warfield, 1977). A functional isomorphism on the other hand requires the functional connectivity between its component entities (Lehar, 2003). It is an extension to Müller's psychophysical postulate (Müller 1896), and Chalmers' principle of structural coherence (Chalmers 1995).

[16] Indeed, experimental evidence suggests that the behavioral or cognitive continuum is a succession of discrete behavioral/cognitive acts performed by an individual (Alexandrov 1999; Madison 2001). Each separate act is the integration of a certain number of operations, which are important and appropriate for the realization of this act. The change from one behavioral/cognitive act to another is embedded in a rapid "transitional process" (Alexandrov 1999). The same is true for the phenomenological structure of human consciousness which consists of stable nuclei (or thoughts) and transitive fringes (or periods) – as it is described by James' metaphor of "Stream of Thoughts" (James 1890). It seems that metastability provides a mechanism of the functional isomorphism realization (Fingelkurts and Fingelkurts 2004).

Fingelkurts 2001). We hypothesize that at this level the OS process binds a number of different properties into an unified unit within one sensory modality, or to use Metzinger's term, into a "perceptual Gestalt" (Metzinger 1995).

However, a perceived object (or scene) usually has several qualities (color, shape, texture, and so on) that are all instantiated at the same time, in the same place. Thus, when we perceive an object, we normally do not see its features apart from each other; instead we perceive a spatially localized unit that has, at the same time, a given color, shape, particular texture, and so on. In other words, we cannot consciously perceive an object as a whole without perceiving it as having a value for each of these sensory qualities. We suppose that the OS processes between different brain regions (indexed through *structural synchrony of segments within EEG field*) serve to bind spatially dispersed representations (bases of sensations) of a multimodal stimulus into an integrated and *unified percept* (Fingelkurts and Fingelkurts 2003). Within the framework of an OA approach, this level of OS corresponds to Metzinger's generation of "multi-modal Gestalts" (Metzinger 1995). Indeed, using a robust illusion known as the McGurk effect[17] (McGurk and MacDonald 1976), it has been shown that the crossmodal binding in the human brain is achieved through the process of operational synchrony between modality-specific and non-specific cortical areas, rather than in so-called convergence regions of the cortex (Fingelkurts et al. 2003a). It is interesting that the multimodal representational percepts obtained in this study had emergent properties. The subjects who did not display the McGurk illusion (meaning that they lack of multi-sensory integration) in contrast demonstrated significant uncoupling (negative values of the operational synchrony) of particular brain areas (see Fingelkurts et al. 2003a, for a discussion). These experimental findings support the view of John (2002) that subjective awareness of the percept emerges as a property of an electrotonic field resonating throughout coherent neuronal masses in the brain. It is further proposed that such a binding process is crucial for awareness and conscious processing (Singer 2001; John 2002), where the "self" may be a transient dynamic signature of a distributed array of many brain regions (a hierarchy of OMs in our interpretation, see Fingelkurts and Fingelkurts 2003) integrated by synchronization (Varela 2000). Functional isomorphism between the dynamical structure of EEG field (sequence of OMs) and the dynamical structure of behavior (sequence of behavioral acts), cognition (sequence of cognitive acts), and phenomenological structure of

---

[17] In this effect normal listeners report hearing audio-visually fusion syllables as some combination of the auditory and visual syllables (e.g., auditory /ba/ + visual /ga/ are perceived as /va/) or as a syllable dominated by the visual syllable (e.g., auditory /ba/ + visual /va/ are perceived as /va/). The vast majority of people (but not all) experience the McGurk illusion. It was also shown that the McGurk illusion exists between other sensory modalities.

consciousness (sequence of metal states or thoughts) is described in detail elsewhere (Fingelkurts and Fingelkurts 2001).

It is worth noting that the sequences of cognitive operations responsible for sensations and their synchronization into complex cognitive operations (which underlie percepts) occur simultaneously (parallel processing), enabling subjective apprehension of a unified holistic experience (Bayne and Chalmers 2002). At the EEG level, the *constancy* and *continuous* existence of metastable OMs persist across a sequence of *discrete* and concatenated segments of stabilized local EEG activities that underlie them (Fig. 3; Fingelkurts and Fingelkurts 2001, 2003). Presented framework suggests that both parallel and serial processing may be just different sides of the same one mechanism – synchrony of brain operations. Parallel processing is performed by individual neuronal assemblies, while serial processing emerges as a result of formation of OMs and their changes along with shifts in the process of actualization of objects in the physical or mental world.

Because of 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; Basar et al. 2001; Basar 2004). Consequently, a large number of functionally distinct OMs can co-exist simultaneously on different brain frequencies and even between them[18] (for experimental support, see Fingelkurts 1998; Kaplan and Shishkin 2000; Fingelkurts et al. 2004b). If signal types can be encoded in characteristic spatial-temporal 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). Thus, most likely the OMs exist simultaneously to subserve the multiple operational acts require by the functioning of the organism and the interaction of the organism with its environment (for similar formulation, see Arbib 2001). However, only some of these OMs may constitute mental states (Fingelkurts and Fingelkurts 2003, 2005). Even though there are many mental images active at any time, consciousness is rather *focused* to a particular mental state in which the potential for many is sacrificed for the "survival" of one[19] (Fingelkurts and Fingelkurts 2001), which can be of

---

[18] 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 et al. 2005).

[19] This point has been emphasized many times during history of psychophysiology science as a "limited capacity of conscious state" (James 1890; Kahneman 1978; Posner 1987; Baars 1988; von der Malsburg 1997).

different complexity, however[20]. We suggest that this level of OS process corresponds to the "formation of complex scenes and situations" though "temporal Gestalts," as Metzinger labeled them (Metzinger 1995). Memory should be involved here, guiding the behavior through representations of the world and thus freeing the individual from environmental dependency.

It has been suggested that synchronization of the operations of certain cortical areas (OMs) seems necessary as a basis for the successful performance of different memory stages: Encoding, retrieval, and retention (Fingelkurts et al. 2003b). Generally, the diversity of OMs and their "recruitment order" (the number of areas involved) grew simultaneously as the cognitive load increased and reached its maximum at the retention stage of the short-term memory task (Fig. 4). Also, the functional life-span of cortical OMs within the anterior part of the cortex became shorter during the retention and test periods of the short-term memory task. This was interpreted as demonstrating a more dynamic performance of synchronized brain operations during retrieval. In contrast, occipital and parietal cortical areas were performing longer operational acts. It is intriguing that although memory encoding, retrieval, and retention often shared common regions of the brain network, the particular functional integration of these areas (indexed as OMs) was unique for each stage of the short-term memory task (for a detailed analysis, see Fingelkurts et al. 2003b). This suggests that the same cortical regions may play a part in more than one functional constellation, and that it is their *interactions* with other brain regions that determine what operations are being served at that time. The fact that different consequent OMs may contain several common areas permits continuity between past, present and future, thus leading to *continuity* of cognitive processes and subjective experiences over several *discrete* microstates. These experimental results are consistent with theoretical conceptualizations of Brown (1998, p. 244), who writes, "The states replace their predecessors in overlapping waves. The sequence of phases in the state is obligatory: an inception, a development, a perishing, giving way to the next state in the series." Thus, "The becoming is absorbed into the present and obscured by the wholeness of the entity it creates" (Brown 1998, p. 239).

In this way the multidimensional and hierarchical Operational Architectonics framework may provide plausible and productive foundations for the fine texture of cognition and consciousness; it shows how discreteness and continuity dynamics can be integrated in order to

---

[20] Complexity hierarchy enables the system to build complex representations from primitive ones so that the semantic value of the complex representation is determined by, and dependent on, the semantic values of the primitives (Fingelkurts and Fingelkurts 2003).

tell a unified story about how the mind works. However, the OA tenets require further systematic experimental investigations and mathematical modeling.

6. Further experiments and predictions

In the context of the OA framework, it has been shown experimentally that there are changes at the neurophysiological level (in the duration and transition speed of operations; and in the number and type of OMs) following changes in the subjects' functional state (Fingelkurts 1998), cognitive tasks (Kaplan and Shishkin 2000), and memory stages (Fingelkurts et al. 2003b). However, previous experiments have not employed explicitly the particular contents of consciousness (the phenomenal level)[21]. Therefore, the next step should be the study where conscious contents have been taken according to the methodology of contrastive analysis (e.g., consciousness as a variable).

We suggest that patients with schizophrenia, who have particular symptoms ("standing thought" or "fast stream of thoughts"), can be used for this purpose. In such patients, the temporal conscious phenomena are manifested in their clearest form and will not be easily confused with any other phenomena, such as faking. The subjective experiences of these patients should be described so that the degree of experienced changes in conscious experience (e.g. the duration of a thought) can be estimated or quantified (Lutz et al. 2002). Multichannel EEG should be registered during "standing thought" and "fast stream of thoughts" conditions separately. The duration of EEG quasi-stationary segments and the set and complexity of OMs should be calculated. Considering that (a) the mean duration of the quasi-stationary segments was consistent with the duration of cognitive processes (Fingelkurts et al. 2003a) and (b) different topographies of the microstates (number/set of OM) were associated with diversity of different cognitive modalities involved (Fingelkurts et al. 2003b), we predict that the life-span/diversity of neuronal correlates (indexed as quasi-stationary segments and OMs) should be longer/lower when such subjects experience "long thoughts", and shorter/higher when they experience "short thoughts" (collaboration is welcomed).

The next experimental step is to test whether the patient's subjective experience of thought duration could be modified pharmacologically to shorten or prolong the subjectively perceived

---

[21] It should be stressed that the concepts "state" and "contents" of consciousness should be differentiated from each other. The "contents" of consciousness refer to the patterns of subjective experience at the phenomenal level: percepts, emotions, sensations, mental images, etc. (Block 1995), while the term "state" of consciousness refers to the underlying context in the brain in which the phenomenal contents of consciousness are realized. Thus, the "state" does not refer to the subjective experiences themselves (Kallio and Revonsuo 2003).

duration of the thought. Multichannel EEG should be registered concurrently, thus permitting the monitoring of the involvement of neural mechanisms (indexed by the duration of quasi-stationary segments and by the number/type of OMs) during the pharmacological influence. It is well known that a number of pharmacological agents create subjective time distortions when administered. For example, nootropic drugs / neuroleptics can be used as pharmacological agents which shorten/prolong the subjectively perceived duration of the thought. It has been shown that these drugs indeed decrease/increase (respectively) the duration of segments of EEG stationary maps (Lehmann et al. 1993; Kinoshita et al. 1995). Therefore, we predict that if the subjective experience of the duration of a thought changes (by means of pharmacology, for example), then the life-span of EEG quasi-stationary segments and the set/complexity of OMs should change correspondingly.

However, the use of pharmacological agents most likely would influence local and remote brain functional connectivity *per se*, thus altering neurophysiological activity itself. Indeed, it has been shown that the activity of different-size neuronal populations within alpha and beta frequency bands is affected significantly by the psychotropic drug lorazepam (Fingelkurts et al. 2004b). It also has been demonstrated that lorazepam leads to a total and significant increase in the number and strength of remote functional connections within both alpha and beta frequency bands along the whole neocortex (Fingelkurts et al. 2004a). Thus, the more productive way to test the previously offered hypothesis is to use hypnosis (even better the posthypnotic suggestion about entering hypnosis[22]) instead of pharmacology to influence thought length. In such an experiment the subject would be given a post-hypnotic suggestion about the duration of his/her thoughts (“standing thought” or an extremely fast stream of thoughts) when given a pre-specified cue. Multichannel EEG should be registered simultaneously with consequent calculation of quasi-stationary segments and OMs. In our preliminary study with a single highly hypnotizable subject in normal baseline condition and under neutral hypnosis we have shown that the duration of EEG quasi-stationary segments (for delta, theta, alpha, and beta frequency bands) was significantly longer during hypnosis when compared with baseline (unpublished data). Even though in that study there was no any hypnotic suggestion about the time experience, the obtained results indirectly support our prediction, – it is well known that during hypnosis the sensation of time passing is stretched because internal events are subjectively slowed (Naish, 2001).

---

[22] The use of a posthypnotic suggestion would minimize the need for suggestions of relaxation, drowsiness, etc. which are typically used in a hypnotic induction (Kallio and Revonsuo 2003).

Another framework that permits to trace neurophysiological changes (indexed as EEG segments and OMs) along with changes in subjectively perceived temporality, is the flash-lag effect (perceptual lagging of a separate reference flash behind the features of a continuously exposed object/event) (Purushothaman et al. 1998). A physiologically plausible explanation of this effect has been suggested within the concept of perceptual acceleration (Bachmann et al. 2003). According to this concept, the latency (with which signals from the same stimulus-event are sampled for explicit representation) is long initially (after the onset of stimulation); however it decreases gradually on-line with temporally extended stimulus input. This may be so, because thalamo-cortical (Bachmann 1984, 1999) and intra-cortical (DiLollo et al. 2000) reentrant processes are involved. That is why there is initially a long delay between the stimulus input and its representation in awareness. However, with an accumulating stream of input signals, obtaining awareness is gradually accelerated, as the preceding samples of stimulation-stream will have prepared retouch ahead in time (Bachmann et al. 2003). The OA framework makes the prediction that in the beginning of such a stimulation-stream, the duration of EEG quasi-stationary segments should be longer than at the end. Concurrently, the "order of recruitment" of OM also should be higher in the beginning, reflecting the nonspecific re-entrant processes. In contrast to continuous in-stream stimulation ahead in time, long EEG segments and diverse OMs should characterize a separate flash. Results from our previous study of multi-sensory standard and deviant congruent and incongruent stimuli (Fingelkurts et al. 2003a) are in line with this prediction. For all deviant stimuli (irrelevant to modality), the duration of brain operations (indexed as EEG segments) was significantly longer than for the standard stimuli, and for audio-visual stimuli the duration of brain operations was significantly shorter than for unimodal stimuli (irrelevant to modality). Also, brain operations (indexed as EEG segments) tended to be of a longer duration in response to the presentation of incongruent audio-visual stimuli than in response to the presentation of congruent audio-visual stimuli (see Fingelkurts et al. 2003a for a discussion).

The OA framework suggests the functional isomorphism between the dynamic phenomenological structure of consciousness and the dynamic structure of bioelectrical brain field (Fingelkurts and Fingelkurts 2001). Thus, another set of experiments should concentrate on studying this isomorphism. Such experiments would contrast the same content of consciousness caused by two different mechanisms: First, for example, by a hypnotic suggestion (e.g. the hallucinatory experience of seeing a particular object) and second, by an actual visual stimulus, by showing the actual object during wakefulness (see Kallio and Revonsuo 2003 for description of several relevant experiments). Multichannel EEG should be registered during these two conditions with subsequent calculation of OMs and duration of EEG quasi-stationary segments. If the functional isomorphism principle is correct, then the same conscious content imposed by hypnotic suggestion and by visual stimulus should be expressed by the same number, set and duration of OMs. Also, experiments in which perceptual experience changes without any change in external stimuli (Multistable illusions or Illusory contours, Eagleman 2001; 3-D object arising autostereograms, Lutz et al. 2002; the Mooney face figures, Rodriguez et al. 1999; or the pop-out effect, Treisman and Gelade 1980) can be used for the same purpose.

The main point of the OA framework is that operational synchrony may represent the binding mechanism (Fingelkurts and Fingelkurts 2001, 2003). Thus, one predicted consequence would be disruption in the OA (measured as the large-scale patterns of neural population coordination, OMs) in patients with schizophrenia as compared to normals. We suppose that such disruption might be related to a fragmented cognitive and phenomenological experience found in schizophrenic patients (Haig et al. 2000). This prediction is supported by the experimental results of a pilot study (Kaplan and Borisov 2002). Therefore, we reasoned that disruption of this coordination mechanism ("a disorder of the metastable balance" as termed by Bressler 2003) is a contributing factor in the disorganization syndrome, a psychopathological dimension in schizophrenia (Cuesta and Peralta 2001). Other patients with disorganization syndromes may also be studied for the same purpose.

This review article was intended to show that OA framework of timing in cognition and its neurobiological (EEG) counterpart provides a neurobiologically plausible explanation and can produce highly specific predictions on brain processes. Such predictions can lead to experiments yielding results that may prove the predictions correct. Even though the OA framework is still incomplete, we argue that there is a sound perspective on further developing the neurobiological approach to account for a problem of "continuity and discreteness" within a unified theoretical framework.

7. Appendix A: Operational Architectonics and other related theoretical frameworks

The OA theoretical framework has a marked resemblance to other theoretical accounts currently dominating the field of research. This is not the place for a detailed discussion of the similarities and differences between various theoretical frameworks, since the scope of the present paper is limited to the "continuity-discreteness" problem. Therefore, we will touch this subject very briefly. The first theory which we want to address is the "Global Workspace

(GW)" framework (Baars 1988). According to this theory, the brain seems to show a distributed style of functioning, in which the detailed work is done by millions of specialized neural groupings without specific instructions from some command centre. Mostly these are unconscious processes; however, consciousness creates widespread access (free from interference) to complex and unconscious systems. Using "theater metaphor," Baars argued that as theatre combines very limited events taking place on stage with a vast audience, consciousness involves limited information that creates access to a vast number of unconscious sources of knowledge (Baars 1997).

Generally, the OA framework is also consistent with the "Framework for Consciousness" suggested by Crick and Koch (2003). The main lines of correspondence are the following: a preamble on the cerebral cortex; the fact, that most cortical areas is sensitive to correlations among correlations being expressed by other cortical areas; the importance of neuronal assemblies; the claim that conscious awareness is a series of discrete snapshots and that the durations of successive snapshots are not constant (Crick and Koch 2003).

Further, our theoretical framework is also compatible with Chalmers' "Philosophy of Mind" (2002) in the part that any distinction in experience should be mirrored by a distinction in neural activity, and the pattern of experience should be matched by the pattern of awareness (see "functional isomorphism" in Fingelkurts and Fingelkurts 2001, 2003, 2004).

It is worth to note that OA framework is in vein with Revonsuo' "Neuroconsciousness" conception (2001). According to this framework, consciousness is a real biological phenomenon that is physically located within the brain; – it is the phenomenal level of brain organization (Revonsuo 2000). Further, it is suggested that physiologically neuroconsciousness consists of large-scale electrophysiological (or bioelectrical) activity spatio-temporal patterns; and synchrony in these patterns may be the mechanism by which the conscious state and its contents are realized in the brain. Further, it has been proposed that "neural synchrony seems to be capable of supporting higher-level electrophysiological entities that resemble the content of the phenomenal level of organization" (Revonsuo 2001, p. 6).

Besides just mentioned theories, there are two related theoretical frameworks which have the closest similarities with the OA conceptualization. These are (a) the "Resonant Cell Assemblies" framework developed by Varela (1995) and (b) the "Dynamic Core" theory proposed by Tononi and Edelman (1998). Because of limited space, we summarize the similarities and differences between these theoretical frameworks and our OA theory in Table 1. One can notice that besides similarities between all three theories, the OA framework has several notable differences. We will concentrate here only on the most relevant ones.

1) Neither the Neuronal Assembly (NA), nor the Dynamic Core (DC) is flexible enough to allow for a representation of complex objects or for the execution of complex combinatorial cognitive operations, which are also the gist of their internal structure. This is so because NA and DC do not have internal hierarchical organizations. Here, it is essentially necessary to allow for hierarchical organization with the structured integration of subcomponents (von der Malsburg 1999). The components in question are often necessarily activated under the same overall conditions; hence without defined internal structure a NA/DC could not distinguish between the two (or more) types of events. In contrast, Operational Modules (OMs), which are

Table 1. Comparison of Operational Architectonics framework with Resonant Cell Assemblies and Dynamical Core frameworks

	Dinamic Core	**Operational Architectonics**	**Resonant Cell Assemblies**
	Tononi & Edelman, 1998	Fingelkurts & Fingelkurts, 2001	Varela, 1995
Definition	The dynamic core (DC) is a functional cluster: its participating neuronal groups are much more strongly interactive among themselves than with the rest of the brain	Operational Module (OM) is a distributed set of the neuronal assemblies, which synchronize their operations in order to participate in the same cognitive act during the period of observation	A neural assembly (NA) is a distributed subset of neurons with strong *anatomical reciprocal* connections
Structure	The DC (functional cluster) is a single, integrated neural process that *cannot be decomposed* into independent or nearly independent components, therefore it does not have internal structure	The OM has rich internal strucutre and therefore *can be decomposed* into independent or nearly independent neuronal assemblies; or it *can be integrated* with other OMs within new complex OM	The NA is a single, integrated neural process that *cannot be decomposed* into independent or nearly independent components, therefore it does not have internal structure
Time-scale	Its global activity patterns must be selected within less than a second out of a very large repertoire.	Its global activity patterns must be selected within less than a second out of a very large repertoire.	Its global activity patterns must be selected within less than a second out of a very large repertoire.
Dynamics	The DC may change in composition over time.	The OM may change in composition over time.	The NA may change in composition over time.
Inclusion criteria	Participation in the DC depends on the rapidly shifting functional connectivity among *neurons* rather than on anatomical proximity	Participation in the OM depends on the rapidly shifting functional connectivity among *neuronal assemblies* rather than on anatomical proximity	Participation in the NA depends on the rapidly shifting functional connectivity among *neurons* rather than on anatomical proximity
Nature	The DC is a process, since it is characterized in terms of time-varying *neural interactions*, not as a thing or a location	The OM is a process, since the continuity of OM exists as long as the set of neuronal assemblies keeps functional synchronicity between their discrete operations on a particular time-scale	The NA is a process, since it is characterized in terms of time-varying *neural interactions*, not as a thing or a location
Relation to the rest of the brain	Different parts of the brain can be jointly part of the DC but the core is not restricted to any particular subset of the brain	Different parts of the brain can be jointly part of the OM but it is not restricted to any particular subset of the brain	Different parts of the brain can be jointly part of the NA but it is not restricted to any particular subset of the brain
Number	The DC is *one*, however certain psychiatric syndromes may be associated with the existence of multiple dynamic cores within one brain	Brain in normal state as well as during different psychiatric syndromes is characterized by the existence of *multiple* OMs within one brain	Author did not address this issue
Metastability	The DC constantly gives rise to new patterns in succession and thus has *metastable* dynamics, however it is *not metastable* by itself	The OM constantly gives rise to new patterns in succession and thus has *metastable* dynamics; additionally it is *metastable by itself* because intrinsic differences in activity between the neuronal assemblies which constitute OM are sufficiently large that they *do their own job*, while still retaining a tendency *to be coordinated* together within single OM	The NA constantly gives rise to new patterns in succession and thus has *metastable* dynamics, however it is *not metastable* by itself

the main constituents of the OA framework, do have such internal organization (see Fingelkurts and Fingelkurts 2003, 2005): one OM may be a member of another more complex one, or it may be decomposed until simple neuronal assemblies, each of which would be responsible for simple brain/cognitive operations. Therefore, the recombination of subsets of neuronal assemblies into OMs, and of different OMs into larger structured OMs yields a vast number of potential combinations needed to represent the multivariability of cognition and eventually consciousness (Fingelkurts and Fingelkurts 2004). Such complex structure of OM is also important for the semantic representations of words with similar meanings, for example, for hyponyms and hyperonyms (Pulvermüller 1999). For instance, it can be shown that between-assembly connections and activity dynamics are a possible basis of semantic associations and/or grammatical phenomena (see Ivancich et al. 1999; Pulvermüller 1999; Fingelkurts and Fingelkurts 2001, 2003 for further discussion).

2) In contrast to NA/DC models, the OA framework supposes large number of coexisting OMs. Considering the composite polyphonic character of the electrical brain field (EEG), this field may be presented as a mixture of many time-scale processes (individual frequency components) (Nunez 2000; Basar et al. 2001; Basar 2004). Consequently, a large amount of functionally distinct OMs can co-exist simultaneously at different time-scales and even between them (Kaplan and Shishkin 2000; Fingelkurts and Fingelkurts 2001; 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). Simultaneous existence of these OMs subserves the numerous operational acts on the functioning of the brain/organism and on the interaction of the organism with its environment (Arbib 2001). Only subset of these OMs constitutes mental states, some of which are of conscious nature (see Fingelkurts and Fingelkurts 2001, 2003, 2005 for further discussion).

3) Even though all three theoretical frameworks stress the importance of functional connections, the concepts they used to define the values of functional connectivity differ significantly between them. This subject is discussed in a grate detail in our previous publications; therefore we address interested reader to them (Fingelkurts et al. 2005; Fingelkurts and Fingelkurts 2005). Here we should only mention that OA framework supposes “true” functional synchrony which not necessarily requires any anatomical connections. It is the stimuli (either external or internal), the task, and other functions which cause the synchronization; therefore, it is a function-based synchronization (Fingelkurts and Fingelkurts 2005).

4) The OMs in contrast to NA/DC are characterized by the metastable nature. Attention, we speak here not about dynamics of OM/NA/DC which is also metastable, but about the functional entity (OM/NA/DC) *pre se*. As we have already mentioned in the main body of the text, the OMs are inherently metastable since they constructed by separate neuronal assemblies which process and represent different types of information from relatively independent brain functional systems; however, at the same time they exhibit tendency for the coordinated activity (Fingelkurts and Fingelkurts 2004, 2005). Such simultaneous existence of autonomous and coordinated tendencies is the essence of the metastable regime of system (brain) functioning (Kelso 1991, 1995).

5) NA/DC are lacking of the time-dimensional information in each cortical area separately, while the OM is based on the detailed and known time-dimensional information in each cortical area.

8. Appendix B: The methodological problems with Cell Assembly model

The claim held by many researches that cell assembly framework cannot be easily falsified may be the basis for a premature rejection of many cell assembly based theories (as the OA theory) that offer a neurobiologically plausible framework within which so much can actually be explained. The existence of cell assemblies could, in principle, be tested by recording, in parallel, multiple neurons whose activity is correlated with different cognitive functions or conscious experience. Multielectrode recordings have already indicated that rapid changes in the functional connectivity among distributed populations of neurons can occur independently of firing rate (Vaadia et al. 1995). Furthermore, recent studies in monkey frontal cortex show abrupt and simultaneous shifts among stationary activity states involving many, but not all recorded neurons (Seidemann et al. 1996), thus clearly indicating the functional clustering of neurons into neuronal assemblies.

However, such studies have several methodological limitations. For example, understanding of how the cooperated activity of neurons gives rise to collective assembly behavior requires improved methods for simultaneous recording with minimal damage to the neuronal tissue (Buzsáki 2004). Another important step in multielectrode recording analysis is the isolation of single neurons on the basis of extracellular features. Several methods exist, however they based on the assumptions which are difficult to justify in most cases (Llinas 1988; Gray et al. 1995). Yet another difficulty is that no independent criteria are available for the assessment of unit isolation (Buzsáki 2004) and therefore, inter-laboratory comparison is difficult and makes interpretation of the results controversial. Additionally, it is often not known what a given cell assembly is coding for: there is considerable evidence that the firing pattern of neurons even in primary sensory cortices reflects not just the physical nature of a stimulus, but also internal factors (Zhou and Fuster 2000).

Additionally, cell assemblies widely distributed over distant cortical regions are obviously difficult to observe through electrophysiological recordings from local neuron clusters or small areas. If large-scale neuronal theories of cognitive functions are correct, then fast, large-scale recording techniques are necessary to visualize activity changes in distributed assemblies. Fortunately, several such new techniques have been already emerged (see for example, Grinvald et al. 2003; Buzsáki 2004; Bennett and Zukin 2004) and therefore there is a hope that the question of whether there are specific cell assemblies for different cognitive operations will be soon answered experimentally (and therefore will give bases for possible falsification of cell assembly based theories).

We should stress also, that among already existed large-scale techniques, EEG and MEG approaches can be extremely useful when new methods of their analysis (as described in the present paper) are used for investigating the cortical topographies of neuronal assemblies. A coherent picture can be drawn already on the basis of a number of studies (see Fingelkurts and Fingelkurts 2004, 2005 for the resent review of research).

It is relevant to point out here that the proposed concept of cell assemblies is necessarily fuzzy. We agree with Pulvermüller (1999) that this is not a problem: “It is essential to see that fuzziness is intrinsic to the assembly concept and that this is only problematic in the way it is a problem to determine the boundaries of the sun or the Milky Way” (Pulvermüller 1999, p. 310). What is important – it is functional discreteness of cell assemblies (Braitenberg 1980; Braitenberg and Pulvermüller 1992). Exactly this main property of neuronal assemblies is used in the OA framework (see Fingelkurts and Fingelkurts 2005).

Acknowledgments

The authors are grateful for stimulating discussions on related questions to Prof. Alexander Kaplan, Prof. Walter Freeman, Prof. Erol Basar, Prof. Hermann Haken, Prof. Steve Bressler, and Mr. Carlos Neves (Computer Science specialist). Conversations with Prof. Antti Revonsuo about neurophysiology of consciousness have had a significant influence on the ideas in this paper. We wish also to thank Prof. William Banks and Prof. Max Velmans for their very useful comments on the earlier version of this paper. The writing of this paper has been supported by the BM-SCIENCE. Special thanks to Prof. Richard Lippa for skilful text editing.

References:

Albertazzi L (1998) Perceptual saliences and nuclei of meaning. In: Poli R (ed). The Brentano Puzzle. Aldershot, Ashgate, pp 113-138

Alexandrov YuI (1999) Psychophysiological regularities of the dynamics of individual experience and the “stream of consciousness.” In: Taddei-Feretti C and Musio C (eds). Series on Biophysics and Biocybernetics. Neural Basis and Psychological Aspects of Consciousness, Vol. 8 – Biocybernetic. World Scientific, Singapore-New Jersey-London-Hongkong, pp 201-219

Allport DA (1968) Phenomenal simultaneity and perceptual moment hypothesis. Br J Psychol 59: 395-406

Alpern M (1952) Metacontrast. Am J Optom 29: 631-646

Andrews TJ, White LE, Binder D, Purves D (1996) Temporal events in cyclopean vision. Proc Natl Acad Sci USA 93: 3689-3692

Arbib MA (2001) Co-evolution of human consciousness and language. In: Marijuan EP (ed). Cajal and Consciousness: Scientific Approaches to Consciousness on the Centential of Ramon y Cajal’s Textura. Vol. 929. Annals of the NYAS, New York, pp. 195-220

Averbeck BB, Lee D (2004) Coding and transmission of information by neural ensembles. Trends Neurosci 27: 225-230

Baars BJ (1988) A cognitive theory of consciousness. Cambridge University Press, New York

Baars BJ (1997) In the theatre of consciousness: Global workspace theory, a rigorous scientific theory of consciousness. J Conscious Stud 4: 292-309

Bachmann T (1984) The process of perceptual retouch: Nonspecific afferent activation dynamics in explaining visual masking. Percept Psychophys 35: 69-84

Bachmann T (1994) Psychophysiology of visual masking. Nova Science, Commack, New York

Bachmann T (1999) Twelve spatiotemporal phenomena, and one explanation. In: Aschersleben G, Bachmann T, Musseler J (eds). Cognitive contributions to the perception of spatial and temporal events. Elsevier, Amsterdam North-Holland, pp 173-206

Bachmann T, Luiga I, Poder E, Kalev K (2003) Perceptual acceleration of objects in stream: Evidence from flash-lag displays. Conscious Cogn 12: 279-297

Bair W (1999) Spike timing in the mammalian visual system. Curr Opin Neurobiol 9: 447-453

Bak P, Tang C, Wiesenfeld K (1987) Self-organized criticality: An explanation of 1/f noise. Phys Rev Lett 59: 364-374

Baker SN, Spinks R, Jackson A, Lemon RN (2001) Synchronization in monkey motor cortex during a precision grip task. I. Task-dependent modulation in single-unit synchrony. J Neurophysiol 85: 869-885

Barrie JM, Freeman WJ, Lenhart MD (1996) Spatiotemporal analysis of prepyriform, visual, auditory, and somesthetic surface EEGs in trained rabbits. J Neurophysiol 76: 520-539

Barsalou LW (1999) Perceptual symbol systems. Behav Brain Sci 22: 577-609

Basar E (2004) Macrodynamics of electrical activity in the whole brain. Int J Bifurcat Chaos 14: 363-381

Basar E (2005) Memory as the “whole brain work.” A large-scale model based on “oscillations in super-synergy.” Int J Psychophysiol 58: 199-226

Basar E, Basar-Eroglu C, Karakas S, Schurmann M (2001) Gamma, alpha, delta, and theta oscillations govern cognitive processes. Int J Psychophysiol 39: 241-248

Bayne T, Chalmers DJ (2002) What is the unity of consciousness? In: Cleeremans A (ed). The unity of consciousness: Binding, integration, dissociation. Oxford Univ Press, URL = http://www.u.arizona.edu/~chalmers/papers/unity.html

Bennett NVL, Zukin RS (2004) Electrical coupling and neuronal synchronization in the mammalian brain. Neuron 41: 495–511

Bickle J, Worley C, Bernstein M (2000) Vector subtraction implemented neurally: A neurocomputational model of some sequential cognitive and conscious processes. Conscious Cogn 9: 117-144

Birch T (2002) Introduction to mental images. Homepage, URL = http://www.gis.net/~tbirch/hp5.html

Blachowicz J (1997) Analog representation beyond mental imagery. J Philos 94: 55-84

Block RA (1990) Models of psychological time. In: Block RA (ed). Cognitive models of psychological time. Erlbaum, Hillsdale, NJ, pp 1-35

Block N (1995) On a confusion about a function of consciousness. Behav Brain Sci 18: 227-287

Bolton TL (1894) Rhythm. Am J Psychol 6: 145-238

Borisov SV (2002) Studying of a phasic structure of the alpha activity of human EEG. PhD dissertation, Moscow: Moscow State Univ, Russian Federation, 213 pp (in Russian)

Braitenberg V (1980) Alcune considerazione sui meccanismi cerebrali del linguaggio. In: Braga G, Braitenberg V, Cipolli C, Coseriu E, Crespi-Reghizzi S, Mehler J, Titone R (eds). L'accostamento interdisciplinare allo studio del linguaggio. Franco Angeli Editore, Braitenberg.

Braitenberg V, Pulvermüller F (1992) Entwurf einer neurologischen Theorie der Sprache. Naturwissenschaften 79: 103–117

Bressler SL (1995) Large-scale cortical networks and cognition. Brain Res Brain Res Rev 20: 288-304

Bressler SL (2003) Cortical coordination dynamics and the disorganization syndrome in schizophrenia. Neuropsychopharmacology 28: S35–S39

Bressler SL, Kelso JAS (2001) Cortical coordination dynamics and cognition. Trends Cogn Sci 5: 26-36

Brodsky BE, Darkhovsky BS (1993) Nonparametric Methods in Change-Point Problems. Kluwer, Dordrecht

Brodsky BE, Darkhovsky BS, Kaplan AYa, Shishkin SL (1999) A nonparametric method for the segmentation of the EEG. Comput Methods Programs Biomed 60: 93-106

Brown JW (1998) Fundamentals of process neuropsychology. Brain Cogn 38: 234–245

Bullock TH (1997) Signals and signs in the nervous system: The dynamic anatomy of electrical activity. Proc Natl Acad Sci USA 94: 1-6

Buzsáki G (2004) Large-scale recording of neuronal ensembles. Nat Neurosci 7:446-451

Buzsáki G, Draguhn A (2004) Neuronal oscillations in cortical networks. Science 304: 1926–1929

Callaway E, Layne RS (1964) Interaction between the visual evoked response and two spontaneous biological rhythms: the EEG alpha cycle and the cardiac arousal cycle. Ann N Y Acad Sci 112: 421-431

Cariani P (1997) Emergence of new signal-primitives in neural systems. Intellectica 2: 95-143

Chafe WL (1994) Discourse, consciousness, and time: The flow and displacement of conscious experience in speaking and writing. Univ of Chicago Press, Chicago

Chalmers DJ (1995) Facing up to the problems of consciousness. J Conscious Stud 2: 200-219

Chalmers DJ (2002) Consciousness and its place in nature. In: Chalmers D (ed). Philosophy of mind: Classical and contemporary readings. Oxford, URL = http://jamaica.u.arizona.edu/~chalmers/papers/nature.html

Chomsky N (1957) Syntactic structures. The Hague, Mouton

Churchland PS, Sejnowski T (1992) The computational brain. MIT Press, Cambridge, MA

Cooper LA (1975) Mental transformation of random two-dimensional shapes. Cognit Psychol 7: 20-43

Crick F, Koch C (2003) A framework for consciousness. Nat Neurosci 6: 119-126

Crone NE, Miglioretti DL, Gordon B, Lesser RP (1998) Functional mapping of human sensorimotor cortex with electrocorticographic spectral analysis. II. Event-related synchronization in the gamma band. Brain 121: 2301-2315

Cuesta MJ, Peralta V (2001) Integrating psychopathological dimensions in functional psychoses: a hierarchical approach. Schizophr Res 52: 215-229

Damasio AR (1994) Descartes' error; emotion, reason and the human brain. Picador, New York

Damasio AR (2000) The feeling of what happens. Body, emotion and the making of consciousness. Vintage, London

Dennett DC (1991) Consciousness explained. Little Brown, Boston and New York

Dennett DC, Kinsbourne M (1995) Time and the observer: The where and when of consciousness in the brain. Behav Brain Sci 15: 183-247

Dietze G (1885) Untersuchungen uber den Umfang des bewusstseins bei regelmässig auf einander folgenden Schalleindrucken. Phil Stud 2 362-393

DiLollo V, Enns JT, Rensink RA (2000) Competition for consciousness among visual events: The psychophysics of reentrant visual processes. J Exp Psychol Gen 129: 481-507

Dinse H (1990) A temporal structure of cortical information processing. Concepts Neurosci 1: 199-238

Dinse H (1994) A time-based approach towards cortical functions: neural mechanisms underlying dynamic aspects of information processing before and after postontogenetic plastic processes. Physica D 75: 129-150

Donald M (1993) Precis of origins of the modern mind: Three stages in the evolution of culture and cognition. Behav Brain Sci 16: 737-791

Eagleman DM (2001) Visual illusions and neurobiology. Nat Rev Neurosci 2: 920-926

Edelman GM, Tononi G (2000) A Universe of consciousness: How matter becomes imagination. Basic Books, New York

Effern A, Lehnertz K, Fernandez G, Grunwald T, David P, Elger CE (2000) Single trial analysis of event related potentials: Non-linear de-noising with wavelets. Clin Neurophysiol 111: 2255-2263

Efron E (1970) The minimum duration of a perception. Neuropsychologia 8: 57-63

Eliasmith C (2000) Is the brain analog or digital? The solution and its consequences for cognitive science. Cogn Sci Q 1: 147-170

Eliasmith C (2001) Attractive and in-discrete: A critique of two putative virtues of the dynamicist theory of mind. Minds Machines 11: 417-426

Eliasmith C (2002) Discreteness and Relevance: A Reply to Roman Poznanski. Minds Machines 12: 437–438

Elul R (1972a) The genesis of the EEG. In: Pfeiffer CC, Smythes JR (eds). International review of neurobiology, Vol. 15. Academic Press, New York, pp 227-272

Elul R (1972b) Randomness and synchrony in the generation of electroencephalogram. In: Petsche H, Brazier MAB (eds). Synchronization of EEG activity in epilepsies. Springer Verlag, Vienna, pp 59-77

Fell J, Kaplan A, Darkhovsky B, Röschke J (2000) EEG analysis with nonlinear deterministic and stochastic methods: A combined strategy. Acta Neurobiol Exp 60: 87-108

Fingelkurts AnA (1998) Time-spatial organization of human EEG segment's structure. PhD Dissertation, Moscow: Moscow State University, Russian Federation 415 pp (in Russian)

Fingelkurts AnA, Fingelkurts AlA (2001) Operational architectonics of the human brain biopotential field: Towards solving the mind-brain problem. Brain Mind 2: 261-296, URL = http://www.bm-science.com/team/art18.pdf

Fingelkurts AnA, Fingelkurts AlA (2003) Operational architectonics of perception and cognition: A principle of self-organized metastable brain states. VI Parmenides workshop – Perception and thinking, Institute of Medical Psychology. April 5-10, Elba/Italy (invited full-text contribution). URL = http://www.bm-science.com/team/art24.pdf

Fingelkurts AnA, Fingelkurts AlA (2004) Making complexity simpler: Multivariability and metastability in the Brain. Int J Neurosci 114: 843-862

Fingelkurts AnA, Fingelkurts AlA (2005) Mapping of the brain operational architectonics. Chapter 2. In: Chen FJ (ed). Focus on Brain Mapping Research. Nova Science Publishers, Inc., pp. 59-98. URL = http://www.bm-science.com/team/chapt3.pdf

Fingelkurts AlA, Fingelkurts AnA, Kaplan AYa (2003) The regularities of the discrete nature of multi-variability of EEG spectral patterns. Int J Psychophysiol 47: 23-41

Fingelkurts AnA, Fingelkurts AlA, Kähkönen SA (2005) Functional connectivity in the brain – is it an elusive concept? Neurosci Biobehav Rev 28: 827-836

Fingelkurts AlA, Fingelkurts AnA, Krause CM, Sams M (2002) Probability interrelations between pre-/post-stimulus intervals and ERD/ERS during a memory task. Clin Neurophysiol 113: 826-843

Fingelkurts AnA, Fingelkurts AlA, Krause CM, Möttönen R, Sams M (2003a) Cortical operational synchrony during audio-visual speech integration. Brain Language 85: 297-312

Fingelkurts AnA, Fingelkurts AlA, Krause CM, Kaplan AYa, Borisov SV, Sams M (2003b) Structural (operational) synchrony of EEG alpha activity during an auditory memory task. NeuroImage 20: 529-542

Fingelkurts AlA, Fingelkurts AnA, Krause CM, Kaplan AYa (2003c) Systematic rules underlying spectral pattern variability: Experimental results and a review of the evidence. Int J Neurosci 113: 1447-1473

Fingelkurts AnA, Fingelkurts AlA, Fingelkurts AnA, Kivisaari R, Pekkonen E, Ilmoniemi RJ, Kähkönen SA (2004a) Enhancement of GABA-related signalling is associated with increase of functional connectivity in human cortex. Hum Brain Mapp 22: 27-39

Fingelkurts AnA, Fingelkurts AlA, Fingelkurts AnA, Kivisaari R, Pekkonen E, Ilmoniemi RJ, Kähkönen SA (2004b) Local and remote functional connectivity of neocortex under the inhibition influence. Neuroimage 22: 1390-1406

Finke RA, Kurtzman HS (1981) Mapping the visual field in mental imagery. J Exp Psychol Gen 110: 501-517

Flohr H (1995) Sensations and brain processes. Behav Brain Res 71: 157-161

Fodor J, Pylyshyn Z (1988) Connectionism and cognitive architecture: A critical analysis. Cognition 28: 3-71

Fraisse P (1978) Time and rhythm perception. In: Carterette EC, Friedman MP (eds). Handbook of perception, Vol. 8. Academic Press, New York, pp 203-254

Fraisse P (1984) Perception and estimation of time. Annu Rev Psychol 35: 1-36

Freeman WJ (1972) Waves, pulses and the theory of neural masses. Prog Theor Biol 2: 87-165

Freeman WJ (1974) A model for mutual excitation in a neuron population in olfactory bulb. IEEE Trans Biomed Eng 21: 350-358

Freeman WJ (2003) Evidence from human scalp electroencephalograms of global chaotic itinerancy. Chaos 13: 1067-1077

Freeman WJ, Barrie JM (1993) Chaotic oscillations and the genesis of meaning in cerebral cortex. The IPSEN foundation symposium on "Temporal Coding in the Brain", Paris, 11 October 1993.

Freeman WJ, Vitiello G (2005) Nonlinear brain dynamics and many-body field dynamics. Electromagn Biol Med 24: 233–241

Freeman WJ, Rogers LJ, Holmes MD, Silbergeld DL (2000) Spatial spectral analysis of human electrocorticograms including the alpha and gamma bands. J Neurosci Methods 95: 111-121

Friston KJ (1997) Transients, metastability and neural dynamics. NeuroImage 5: 164-171

Friston K (2000) The labile brain. I. Neuronal transients and nonlinear coupling. Philos Trans R Soc Lond B Biol Sci 355: 215-236

Galambos R, Makeig S, Talmachoff PJ (1981) A 40-Hz auditory potential recorded from the human scalp. Proc Natl Acad Sci USA 78: 2643-2647

Galin D (1994) The structure of awareness: Contemporary applications of William James' forgotten concept of "the fringe." J Mind Behav 15: 375-402

Galin D (2000) Comments on Epstein's neurocognitive interpretation of William James's model of consciousness. Conscious Cogn 9: 576-583

Geissler H-G (1987) The temporal architecture of central information processing: evidence for a tentative time-quantum model. Psychol Res 49: 99-106

Geissler H-G (1997) Is there a way from behavior to non-linear brain dynamics? On quantal periods in cognition and the place of alpha in brain resonances. Int J Psychophysiol 26: 381-393

Geissler H-G, Schebera F-U, Kompass R (1999) Ultra-precise quantal timing: evidence from simultaneity thresholds in long-range apparent movement. Percept Psychophys 61: 707-726

Gho M, Varela FJ (1988) A quantitative assessment of the dependency of the visual temporal frame upon the cortical rhythm. Am J Physiol 83: 95-101

Giaquinta A, Argentina M, Velarde MG (2000) A simple generalized excitability model mimicking salient features of neuron dynamics. J Stat Phys 101: 665-678

Glicksohn J (2001) Temporal cognition and the phenomenology of time: A multiplicative function for apparent duration. Conscious Cogn 10: 1-25

Gobet F, Lane PCR, Croker S, Cheng PC-H, Oliver I, Pine JM (2001) Chanking mechanisms in human learning. Trends Cogn Sci 5: 236-243

Gomes G (2002) Problems in the timing of conscious experience. Conscious Cogn 11: 191–197

Gray CM, Singer W (1989) Stimulus-specific neuronal oscillations in orientation columns of cat visual cortex. Proc Natl Acad Sci USA 86: 1698-1702

Gray CM, Maldonado PE, Wilson M, McNaughton B (1995) Tetrodes markedly improve the reliability and yield of multiple single-unit isolation from multi-unit recordings in cat striate cortex. J Neurosci Methods 63: 43-54

Grinvald A, Arieli A, Tsodyks M, Kenet T (2003) Neuronal assemblies: single cortical neurons are obedient members of a huge orchestra. Biopolymers 68: 422–436

Habel Ch (1994) Discreteness, finiteness, and the structure of topological spaces. In: Eschenbach C, Habel Ch, Smith B (eds). Topological foundations of cognitive science. Report 37. Graduiertenkolleg Kognitionswissenschaft Hamburg, Hamburg, pp 81-90

Haig AR, Gordon E, De Pascalis V, Meares RA, Bahramali H, Harris A (2000) Gamma activity in schizophrenia: evidence of impaired network binding? Clin Neurophysiol 111: 1461-1468

Haken H (1996) Principles of brain functioning: A synergetic approach to brain activity, behavior and cognition. Springer, Berlin

Harter MR (1967) Excitability cycles and cortical scanning: a review of two hypothesis of cortical intermittency in perception. Psychol Bull 68: 47-55

Hasty J, Collins JJ, Wiesenfeld K, Grigg P (2001) Wavelets of excitability in sensory neurons. J Neurophysiol 86: 2097–2101

Hebb DO (1949) The organization of behavior. Wiley, New York

Hill C (1991) Sensations: A defense of type materialism. Cambridge University Press, New York Cambridge University Press.

Hirsh IJ, Sherrick CEJ (1961) Perceived order in different sense modalities. J Exp Psychol 62: 423-432

Hobson JA (1992) A new model of brain-mind state: Activation level, input source, and mode of processing (AIM). In: Antrobus J, Bertini M (eds). The neuropsychology of dreaming sleep. Lawrence Erlbaum Associates.

Hobson JA, Pace-Schott EF, Stickgold R (2000) Dreaming and the brain: Toward a cognitive neuroscience of conscious states. Behav Brain Sci 23: 793-842

Hwa RC, Ferree T (2002) Scaling properties of fluctuations in the human electroencephalogram. Phys Rev E Stat Nonlin Soft Matter Phys 66: 021901

Ivancich JE, Huyck CR, Kaplana S (1999) Cell assemblies as building blocks of larger cognitive structures. Behav Brain Sci 22: 292-293

Izhikevich EM (1999) Class 1 neural excitability, conventional synapses, weakly connected networks, and mathematical foundations of pulse-coupled models. IEEE Trans Neural Netw 10: 499-507

James W (1890) The principles of psychology. Vol. I. Dover, New York

Jansen BH, Cheng WK (1988) Structural EEG analysis: an explorative study. Int J Biomed Comput 23: 221-237

Jeannerod M (1994) The representing brain: Neural correlates of motor intention and imagery. Behav Brain Sci 17: 187-245

John ER (1990) Machinery of the mind. Birkhauser, Boston, MA

John ER (2001) A field theory of consciousness. Conscious Cogn 9-10: 184-213

John ER (2002) The neurophysics of consciousness. Brain Res Brain Res Rev 39: 1-28

Kahneman D (1978) Attention and effort. Prentice Hall, Englewood Cliffs, NJ

Kaplan AYa (1995) On the frame architecture of central information processing: EEG analysis. The Fourth IBRO World Congress of Neuroscience (p 438)

Kaplan AYa (1998) Nonstationary EEG: Methodological and experimental analysis. Usp Fiziol Nauk (Success in Physiological Sciences), 29, 35-55 (in Russian)

Kaplan AYa (1999) The problem of segmental description of human electroencephalogram. Human Physiol 25: 107-114, (Translated from Physiol. Cheloveka)

Kaplan AYa, Shishkin SL (2000) Application of the change-point analysis to the investigation of the brain's electrical activity. Chapter 7. In: Brodsky BE, Darkhovsky BS (eds). Nonparametric statistical diagnosis: Problems and methods. Kluwer Academic Publishers, Dordrecht (the Netherlands), pp 333-388

Kaplan AYa, Borisov SV (2002) The differences in structural synchrony of the brain electrical field in alpha range between normal control and schizophrenic adolescents. Human Brain Mapping Meeting (Sendai, Japan, 2002). Poster No.: 10472. NeuroImage No 329

Kaplan AYa, Borisov SV (2003) Dynamic properties of segmental characteristics of EEG alpha activity in rest conditions and during cognitive load. Zh Vyssh Nerv Deiat Im IP Pavlova (IP Pavlov Journal of Higher Nervous Activity) 53: 22-32 (in Russian)

Kaplan AYa, Fingelkurts AlA, Fingelkurts AnA, Darkhovsky BS (1997) Topological mapping of sharp reorganization synchrony in multichannel EEG. Am J Electroneurodiagnostic Technol 37: 265-275

Kaplan AYa, Fingelkurts AnA, Fingelkurts AlA, Borisov SV, Darkhovsky BS (2005) Nonstationary nature of the brain activity as revealed by EEG/MEG: Methodological, practical and conceptual challenges. Signal Processing 85: 2190-2212

Kallio S, Revonsuo A (2003) Hypnotic phenomena and altered states of consciousness: A multilevel framework of description and explanation. Contemp Hypn 20: 111-164

Kelso JAS (1991) Behavioral and neural pattern generation: The concept of Neurobehavioral Dynamical System (NBDS). In: Koepchen HP (ed). Cardiorespiratory and motor coordination. Springer-Verlag, Berlin

Kelso JAS (1995) Review of dynamic patterns: The self-organization of brain and behavior. MIT Press, Cambridge, MA

Kinoshita T, Strik WK, Michel CM, Yagyu T, Saito M, Lehmann D (1995) Microstate segmentation of spontaneous multichannel EEG map series under diazepam and sulpiride. Pharmacopsychiatry 28: 51-55

Kirillov AB, Makarenko VI (1991) Metastability and phase transition in neural networks: statistical approach. In: Holden AV, Kryukov VI (eds). Neurocomputers and attention, Vol. 2. Manchester University Press, Manchester, pp 825-922

Koenig T, Lehmann D (1996) Microstates in language-related brain potentials show noun-verb differences. Brain Language 53: 169-182

Koenig T, Prichep L, Lehmann D, Sosa PV, Braeker E, Kleinlogel H, Isenhart R, John ER (2002) Millisecond by millisecond, year by year: Normative EEG microstates and developmental stages. NeuroImage 16: 41-48

Köhler W (1940) Dynamics in psychology. Grove Press, New York

Korb KB (1993) Stage effects in the Cartesian theater: A review of Daniel Dennett's consciousness explained. PSYCHE 1(4), December 1993, URL = http://psyche.cs.monash.edu.au/v1/psyche-1-04-korb.html

Kosslyn SM (1975) Information representation in visual images. Cognit Psychol 7: 341-370.

Kristofferson AB (1967) Successiveness discrimination as a two-state, quantal process. Science 158: 1337-1339

Landa P, Gribkov D, Kaplan A (2000) Oscillatory processes in biological systems. In: Malik SK, Chandrashekaran MK, Pradhan N (eds). Nonlinear phenomena in biological and physical sciences. Indian National Science Academy, New Deli, pp 123-152

Laskaris NA, Ioannides AA (2001) Exploratory data analysis of evoked response single trials based on minimal spanning tree. Clin Neurophysiol 112: 698–712

Latour PL (1967) Evidence of internal clocks in the human operator. Acta Psychol 27: 341-348

Lehar S (2003) Gestalt isomorphism and the primacy of subjective conscious experience: A gestalt bubble model. Behav Brain Sci 26: 375-408

Lehmann D (1971) Multichannel topography of human alpha EEG fields. Electroencephalogr Clin Neurophysiol 31: 439-449

Lehmann D, Koenig T (1997) Spatio-temporal dynamics of alpha brain electric fields, and cognitive modes. Int J Psychophysiol 26: 99-112

Lehmann D, Ozaki H, Pal I (1987) EEG alpha map series: Brain micro-states by space oriented adaptive segmentation. Electroencephalogr Clin Neurophysiol 67: 271-288

Lehmann D, Wackermann J, Michel CM, Koenig T (1993) Space-oriented EEG segmentation reveals changes in brain electric field maps under the influence of a nootropic drug. Psychiatry Res. Neuroimaging 50: 275-282

Lehmann D, Strik WK, Henggeler B, Koenig T, Koukkou M (1998) Brain electrical micro-states and momentary conscious mind states as building blocks of spontaneous thinking. I. Visual imagery and abstract thoughts. Int J Psychophysiol 29: 1-11

Lennie P (1998) Single units and visual cortical organization. Perception 27: 889-935

Leznik E, Makarenko V, Llinas R (2002) Electrotonically mediated oscillatory patterns in neuronal ensembles: An in vitro voltage-dependent dye-imaging study in the inferior olive. J Neurosci 22: 2804-2815

Libet B, Wright EW, Feinstein B, Pearl DK (1979) Subjective referral of the timing for a conscious sensory experience. Brain 102: 193-224

Libet B, Gleason CA, Wright EW, Pearl DK (1983) Time of conscious intention to act in relation to onset of cerebral activity (readiness potential): The unconscious initiation of a freely voluntary act. Brain 106: 623–642

Linkenkaer-Hansen K, Nikouline VM, Palva JM, Iimoniemi RJ (2001) Long-range temporal correlations and scaling behavior in human brain oscillations. The Journal of neuroscience 15: 1370-1377

Llinas R (1988) The intrinsic electrophysiological properties of mammalian neurons: insights into central nervous system function. Science 242: 1654-1664

Llinas R, Ribary U (1998) Temporal conjunction. In: Thalamocortical transactions. Consciousness: At the frontiers of neuroscience (Advances in Neurology), Vol. 77. Lippincott-Raven, Philadelphia, pp 213-217

Llinas R, Ribary U, Contreras D, Pedroarena C (1998) The neuronal basis for consciousness. Philos Trans R Soc Lond B Biol Sci 353: 1841-1849

Llinas R, Leznik E, Urbano FJ (2002) Temporal binding via cortical coincidence detection of specific and nonspecific thalamocortical inputs: A voltage-dependent dyeimaging study in mouse brain slices. Proc Natl Acad Sci USA 99: 449-454

Luria AR (1980) Higher cortical functions in man. Kluwer Academic Publishers

Lutz A, Lachaux J-P, Martinerie J, Varela JF (2002) Guiding the study of brain dynamics by using first-person data: Synchrony patterns correlate with ongoing conscious states during a simple visual task. Proc Natl Acad Sci USA 99: 1586-1591

Makarenko V, Llinas R (1998) Experimentally determined chaotic phase synchronization in a neuronal system. Proc Natl Acad Sci USA 95: 15747-15752

Makarenko VI, Welsh JP, Lang EJ, Llinas R (1997) A new approach to the analysis of multidementional neural activity: Markov random fields. Neural Netw 10: 785-789

Mangan BB (1993a) Taking phenomenology seriously: The “fringe” and its implications for cognitive research. Conscious Cogn 2: 89-108

Mangan BB (1993b) Some philosophical and empirical implications of the fringe. Conscious Cogn 2: 142-154

McGurk H, MacDonald JW (1976) Hearing lips and seeing voices. Nature 264: 746-748

McIntosh AR (1999) Mapping cognition to the brain through neural interactions. Memroy 7: 523-548

McIntosh AR, Fitzpatrick SM, Friston KJ (2001) On the marriage of cognition and neuroscience. NeuroImage 14: 1231-1237

Medison G (2001) Functional modeling of the human timing mechanism. PhD Dissertation, Uppsala: Acta Universitatis Upsaliensis, Sweden, 77 pp

Meyer DE, Yantis S, Osman AM, Smith JEK (1985) Temporal properties of human information processing: tests of discrete versus continuous models. Cognit Psychol 17: 445-518

Metzinger T (1995) Faster than thought. Holism, homogeneity and temporal coding. In: Metzinger T (ed). Conscious experience. Imprint Academic and Paderborn, Thorverton, UK, URL = http://www.imprint.co.uk/online/Metz1.html

Michon JA (1985) The complete time experiencer. In: Michon JA (ed). Time, mind, and behavior. Springer-Verlag, Berlin, pp 20-52

Müller GE (1896) Zur psychophysik der gesichtsempfindungen. Z Psychol 10: 1-82

Naish P (2001) Hypnotic time perception: Busy beaver or tardy timekeeper. Contemp Hypn 18: 87–99

Newman J (1995) Thalamic contributions to attention and consciousness. Conscious Cogn 4: 172-193

Noë A, Thompson E (2004) Are there neural correlates of consciousness? J Conscious Stud 11: 3-28

Nunez PL (1995) Neocortical dynamics and human EEG rhythms. Oxford University Press, New York

Nunez PL (2000) Toward a quantitative description of large-scale neocortical dynamic function and EEG. Behav Brain Sci 23: 371-398

O'Brien G, Opie J (1999) A Connectionist Theory of Phenomenal Experience. Behav Brain Sci 22: 127-148

Pascual-Marqui R, Michel C, Lehmann D (1995) Segmentation of brain electrical activity into microstates. IEEE Trans Biomed Eng 42: 658-665

Pelliomisz A, Llinas R (1985) Tenzor network theory of the metaorganization of fanctional geometries in the central nervous system. Neuroscience 16: 245-273

Pöppel E (1988) Mindworks: time and conscious experience. Harcourt Brace Jovanovich, Boston

Pöppel E (1996) Reconstruction of subjective time on the basis of hierarchically organized processing system. In: Pastor MA, Arteida J (eds). Time, internal clocks and movement. Elsevier Science, New York, pp 165-185

Pöppel E (1997) A Hierarchical Model of Temporal Perception. Trends Cogn Sci 1: 56-61

Pouget A, Dayan P, Zemel R (2000) Information processing with population codes. Nat Rev Neurosci 1: 125-132

Posner MI (1987) Chronometric exploration of mind. Erlbaum, Hillsdale, NJ

Poznanski RR (2002) Dendritic integration in a recurrent network. J Integr Neurosci 1: 69-99

Pylyshyn ZW (2002) Mental imagery: In search of a theory. Behav Brain Sci 25: 157–238

Pulvermüller F (1999) Words in the brain's language. Behav Brain Sci 22: 253–336

Purpura DP (1972) Functional studies of thalamic internuclear interactions. Brain Behav 6: 203-234

Purushothaman G, Patel SS, Bedell HE, Ögmen H (1998) Moving ahead through differential visual latency. Nature 396: 424

Rensing L, Meyer-Grahle U, Ruoff P (2001) Biological timing and the clock metaphor: Oscillatory and hourglass mechanisms. Chronobiol Int 18: 329-369

Revonsuo A (1993) Dennett and dissociations of consciousness. Psycoloquy: 4(59), Split Brain (4), URL = http://psycprints.ecs.soton.ac.uk/archive/00000353/

Revonsuo A (2000) Prospects for a scientific research program on consciousness. In: Metzinger T (ed). Neural correlates of consciousness. MIT Press, Cambridge, MA, pp 57-75

Revonsuo A (2001) Can functional brain imaging discover consciousness in the brain? J Conscious Stud 8: 3-23

Reynolds JH, Desimone R (1999) The role of neural mechanisms of attention in solving the binding problem. Neuron 24: 19-29, 111-125

Robins C, Shepard RN (1977) Spatio-temporal probing of apparent rotational movement. Percept Psychophys 22: 12-18

Rodriguez E, George N, Lachaux JP, Martinerie J, Renault B, Varela FJ (1999) Perception's shadow: Long-distance synchronization of human brain activity. Nature 397: 430-433

Sahraie A, Weiskrantz L, Barbur IL, Simmone A, Williams SC, Brammer MJ (1997) Pattern of neocortical activity associated with conscious and unconscious processing of visual signals. Proc Natl Acad Sci USA 94: 9406-9411

Seidemann E, Meilijson I, Abeles M, Bergman H, Vaadia E (1996) Simultaneously recorded single units in the frontal cortex go through sequences of discrete and stable states in monkeys performing a delayed localization task. J Neurosci 16: 752-768

Shallice T (1964) The detection of change and the perceptual moment hypothesis. Br J Stat Psychol 17: 113-135

Shannon C (1948/1949) A mathematical theory of communication. In: Shannon C, Weaver W (eds). The mathematical theory of communication. University of Illinois Press, Urbana, IL, pp 623-656

Shevelev IA, Kostelianetz NB, Kamenkovich VM, Sharaev VA (1991) EEG alpha-wave in the visual cortex: check of the hypothesis of the scanning process. Int J Psychophysiol 11: 195-201

Shevelev IA, Kamenkovich VM, Bark ED, Verkhlutov VM, Sharaev VA, Mikhailova ES (2000) Visual illusion and traveling alpha waves produced by flicker at alpha frequencies. Int J Psychophysiol 39: 9-20

Shishkin SL, Darkhovsky BS, Fingelkurts AlA, Fingelkurts AnA, Kaplan AYa (1998) Interhemispheric synchrony of short-term variations in human EEG alpha power correlates with self-estimates of functional state. Proceedings of 9-th world congress of psychophysiology, Tvaormin, Sicily/Italy, pp 133

Shepard RN, Metzler J (1971) Mental rotation of three-dimensional objects. Science 191: 701-703.

Singer W (2001) Consciousness and the binding problem. Ann N Y Acad Sci 929: 123-146

Singer W, Engel AK, Kreiter AK, Munk MHJ, Neuenschwander S, Roelfsema PR (1997) Neural assemblies: necessity, signature and detectability. Trends Cogn Sci 1: 252-261

Skinner JE, Molnar M (2000) "Response Cooperativity": a sign of a nonlinear neocortical mechanism for stimulus-binding during classical conditioning in the act. In: Malik SK, Chandrashekaran MK, Pradhan N (eds). Nonlinear phenomena in biological and physical sciences. Indian National Science Academy, New Deli, pp 223-248

Sternberg A (1969) The discovery of processing stages: extansions of Donders' method. Acta Psychol 30: 276-315

Strik WK, Lehmann D (1993) Data-determined window size and space-oriented segmentation of spontaneous EEG map series. Electroencephalogr Clin Neurophysiol 87: 169-174

Stroud JM (1955) The fine structure of psychological time. In: Quastler H (ed). Information theory in psychology: problems and methods. The Free Press, Glencoe, Ill, pp 174-205

Suber P (1988) What is software? J Speculative Philos 2: 89-119

Surwillo WW (1966) Time perception and the "internal clock": some observations on the role of the electroencephalogram. Brain Res 2: 390-392

Taylor K (2001) Applying continuous modelling to consciousness. J Conscious Stud 8: 45-60

Tononi G, Edelman GM (1998) Consciousness and complexity. Science 282: 1846-1851

Tonnelier A (2005) Categorization of neural excitability using threshold models. Neural Comput 17: 1447–1455

Treisman A, Gelade G (1980) A feature-integration theory of attention. Cognit Psychol 12: 97-136

Treisman M (1963) Temporal discrimination and the indifference interval: implications for a model of the "internal clock." Psychol Monogr 77: 1-31

Treisman M (1984) Temporal rhythms and cerebral rhythms. Ann N Y Acad Sci 423: 542-565

Treisman M, Faulker A, Naish PL, Brogan D (1990) The internal clock: evidence for a temporal oscillator underlying time perception with some estimates of its characteristic frequency. Perception 19: 705-743

Treisman M, Cook N, Naish PL, MacCrone JK (1994) The internal clock: electroencephalographic evidence for oscillatory processes underlying time perception. Q J Exp Psychol A 47: 241-289

Triesch J, von der Malsburg C (2001) Democratic integration: Self-organized integration of adaptive cues. Neural Comput 13: 2049-2074

Truccolo WA, Ding M, Knuth KH, Nakamura R, Bressler S (2002) Trial-to-trial variability of cortical evoked responses: implications for analysis of functional connectivity. Clin Neurophysiol 113: 206-226

Tsuda I (2001) Toward an interpretation of dynamic neural activity in terms of chaotic dynamical systems. Behav Brain Sci 24: 793-810

Uhr L (1994) Digital and analog microcircuit and sub-net structures for connectionist networks. In: Honavar V, Uhr L (eds). Artificial intelligence and neural networks: Steps toward principled integration. Academic Press, Boston, MA, pp 341-370

Vaadia E, Haalman I, Abeles M, Bergman H, Prut Y, Slovin H, Aertsen A (1995) Dynamics of neuronal interactions in monkey cortex in relation to behavioural events. Nature 373: 515-518

Vanagas V (1994) Active, hierarchical visual system organization and attentional information processing. In: 39. Internationales Wissenschaftliches Kolloquium. Tehnische Universitat Ilmenau, Thüringen, Band 2, pp 91-94

van Gelder T (1995) What might cognition be, if not computation? J Philos XCI: 345-381

VanRullen R, Koch C (2003) Is perception discrete or continuous? Trends Cogn Sci 7: 207-213

Varela FJ (1995) Resonant cell assemblies: A new approach to cognitive functions and neuronal synchrony. Biol Res 28:81-95

Varela FJ (2000) Neural synchrony and consciousness: Are we going somewhere? Conscious Cogn 9: S26-S27

Varela FJ, Toro A, John ER, Schwartz EL (1981) Perceptual framing and cortical alpha rhythm. Neuropsychologia 19: 675-686

Varela F, Lachaux J-P, Rodriguez E, Martinerie J (2001) The brainweb: Phase synchronization and large-scale integration. Nat Rev Neurosci 2: 229-239

Vartanyan GA, Pirogov AA, Konstantinov KV (1989) Changes produced in neuronal excitability by subthreshold depolarization as a possible mechanism of interval selective relationships within the central nervous system. Neurophysiol 21: 201–208

Velmans M (2002) How could conscious experience affect brains? J Conscious Stud 9: 3–29

Venables PH (1960) Periodicity in reaction time. Br J Psychol 51: 37-43

von Baer KE (1864) Welche Auttasung der lebendigen Natur ist die richtige? Und wie ist diese Auttasung auf die Entomologie auzuwenden? In: Schmitzdorff H (ed). Reden gehalten in wiss. Versammlungen und kleine Aufsätze vermischten Inhalts. Verlag der kaiserl, Hofbuchhandlung, S:t Petersburg, pp 237-287

von der Malsburg C (1981) The correlation theory of brain function. Max-Planck-Institut für Biophysikalische Chemie, Postfach 2841, D-3400 Göttingen, FRG

von der Malsburg C (1997) The coherence definition of consciousness. In: Ito M, Miyashita Y, Rolls ET (eds). Cognition, Computation and Consciousness. Oxford Univ Press, Oxford, pp 193-204

von der Malsburg C (1999) The what and why of binding: The modeler's perspective. Neuron 24: 95-104

von Rospatt A (1995) The Buddhist Doctrine of Momentariness: A survey of the origins and early phase of this doctrine up to Vasubandhu. Franz Steiner Verlag, Stuttgart

Warfield JN (1977) Crossing theory and hierarchy mapping. IEEE Trans Syst Man Cybern 7: 505-523

Watson C (2003) MRI cytoarchitectonics: The next level? J Neurol Sci 211: 1-3

White C, Harter MR (1969) Intermittency in reaction time and perception, and evoked response correlates of image quality. Acta Psychol 30: 368-377

Wiener N (1961) Cybernetics: or control and communication in the animal and the machine, 2nd edn. MIT Press, MA

Wright JJ, Robinson PA, Rennie CJ, Gordon E, Bourke PD, Chapman CL, Hawthorn N, Lees GJ, Alexander D (2001) Toward an integrated continuum model of cerebral dynamics: the cerebral rhythms, synchronous oscillation and cortical stability. Biosystems 63: 71-88

Zeki S (2003) The disunity of consciousness. Trends Cogn Sci 7: 214-218

Zhou YD, Fuster JM (2000) Visuo-tactile cross-modal associations in cortical somatosensory cells. Proc Natl Acad Sci USA 97: 9777–9782