

*Below is the unedited draft of the article that has been accepted for publication  
(© Brain Research, 2012, V. 1428, P. 80-92.)*

## **“Machine” Consciousness and “Artificial” Thought: An Operational Architectonics Model Guided Approach**

**Andrew A. Fingelkurts<sup>a,\*</sup>, Alexander A. Fingelkurts<sup>a</sup>, Carlos F.H. Neves<sup>a</sup>**

<sup>a</sup>*BM-Science – Brain and Mind Technologies Research Centre, Espoo, Finland*

### **A B S T R A C T**

Instead of using low-level neurophysiology mimicking and exploratory programming methods commonly used in the machine consciousness field, the hierarchical Operational Architectonics (OA) framework of brain and mind functioning proposes an alternative conceptual-theoretical framework as a new direction in the area of model-driven machine (robot) consciousness engineering. The unified brain-mind theoretical OA model explicitly captures (though in an informal way) the basic essence of brain functional architecture, which indeed constitutes a theory of consciousness. The OA describes the neurophysiological basis of the phenomenal level of brain organization. In this context the problem of producing man-made “machine” consciousness and “artificial” thought is a matter of duplicating all levels of the operational architectonics hierarchy (with its inherent rules and mechanisms) found in the brain electromagnetic field. We hope that the conceptual-theoretical framework described in this paper will stimulate the interest of mathematicians and/or computer scientists to abstract and formalize principles of hierarchy of brain operations which are the building blocks for phenomenal consciousness and thought.

**Keywords:** Operational Architectonics, robot, artificial mind, brain architecture, conscious operation, many-body field dynamics, EEG, metastability.

**Abbreviations:** EEG: electroencephalography; IPST: brain internal physical space-time; OA: operational architectonics; OM: operational module; OST: operational space-time; NE: neuromorphic engineering; PST: phenomenal space-time; SP: synthetic phenomenology.

## 1. Introduction

“Can machines think?” this confusing (at the time) question was raised by a mathematician and computer scientist, Alan Turing (1950); philosophers, however, have debated this issue since the early 17th century. The first serious philosophical consideration of making a *practical* assault on the problem of machine consciousness was made by Leonard Angel (1989) in his book “How to Build a Conscious Machine”. Since then the idea of machine consciousness had progressed from being an interesting philosophical diversion to a real possibility (Holland, 2003a).

The aim of the present paper is to describe a conceptual-theoretical architecture (within the framework of Operational Architectonics of brain and mind functioning) that a computing system (robot) could implement (after appropriate formalization would be achieved) to simulate the operational level in which consciousness and thinking would *self-emerge*. We will use an informal way of description (modeling aspects and computational counterparts are largely still to be devised by mathematicians and/or computer scientists). The lack of technical detail would also be helpful at maintaining intelligibility for the broad audience of this Special Issue. We see this paper as an opportunity to make readers of the journal more aware of the conceptual problems hampering progress in the “machine consciousness” research. In connection with this the most important drawbacks of the existing implementations in an attempt to approach the consciousness phenomenon will be discussed. A previous our article on a related subject has developed briefly the theory-guided approach to artificial consciousness and discussed some general philosophical aspects that relate to this issue (Fingelkurts et al., 2009a).

In the last twenty years there has been an increased interest towards the field of artificial consciousness and related “synthetic” rational thinking (Minsky, 1991, 2006; McCarthy, 1995; Aleksander, 2001; Holland, 2003b; Adami, 2006; Chella and Manzotti, 2007). On the one hand such interest has been stimulated by hopes of being able to design a true conscious machine; on the other hand it has been thought that the actual implementation of conscious thinking in an artificial model could be helpful for a better understanding of consciousness as a phenomenon per se (Denham, 2002). This common optimism is best expressed by Christof Koch (2001): “...we know of no fundamental law or principle operating in this universe that forbids the existence of subjective feelings in artefacts designed or evolved by humans.”

Several researchers, engineers and computer scientists have already began to address the subject by designing and implementing models for artificial consciousness (referred to as “machine consciousness” or “synthetic consciousness”). However, almost all of them take a more or less conventional computational or low-level neurally inspired (anatomical) approach (Fingelkurts et al.,

2009a). The latter approach, named neuromorphic engineering (NE) by Carver Mead in the late 1980s, was suggested to describe and build electronic neural systems whose architecture and design principles mimic biological neural cells and anatomical architectures (Mead, 1989).

During the last decade NE scientists have made substantial progress by designing silicon neurons and synapses (Indiveri et al., 2006; Wijekoon and Dudek, 2008), silicon cochleas and retinas (Chan et al., 2006; Lichtsteiner et al., 2008), and distributed multichip systems of sensors that communicate using neurone-spike-like signals (Chicca et al., 2007; Merolla et al., 2007). Today, however, as noted by Indiveri et al. (2006), NE stands before a large conceptual challenge that must be resolved before any significant progress toward an age of genuinely conscious neuromorphic machines can be made. This challenge is to bridge the gap from systems (machines) that merely mimic or simulate cognitive processes usually correlated with consciousness (so-called Weak Artificial Consciousness, Holland, 2003b; Seth, 2009) to ones that are genuinely conscious (Strong Artificial Consciousness, Holland, 2003b; Seth, 2009). An important practical matter related to this challenge is that a “conscious machine” should be seen as a man-made artificial system (e.g., robot) that enjoys *subjective phenomenal experiences* and related *rational thinking* (Fingelkurts et al., 2009a). Phenomenology is the study of consciousness founded by German philosopher Edmund Husserl (1901/1973) who defined it as: “The reflective study of the essence of consciousness as experienced from the first-person point of view”. Accordingly, the key to developing synthetic consciousness is to develop an agent that, perhaps due to its own complexity combined with a need to self-monitor, would find a use for thinking of itself (or others) as having experiential states.

However, from the point of view of an artificial intelligence engineer “most of the existing theories of consciousness, which typically come from philosophy or psychology, do not provide a fully plausible explanation of what a conscious being is and how consciousness could be produced in a machine. Instead, they offer a more or less *metaphorical* description of consciousness, but not a model that can be directly implemented in computational terms” (Arrabales et al., 2009). One of the most known examples of a heavy usage of metaphor in consciousness theorizing is the Global Workspace (GW) theory developed by Baars (1988). This cognitively-guided theory aims to characterize several consciousness-related phenomena using a theatre metaphor (Baars, 1997). Unfortunately, use of metaphor makes the underlying argument(s) unclear and multiple interpretations are possible. Another popular theory is the information integration theory of consciousness developed by Tononi (2004). This theory argues that subjective experience is one and the same thing as a system’s capacity to integrate information. It states further that the quantity of consciousness available to a system can be measured as the  $\Phi$  value of a complex of elements. However, it has been calculated by Gamez (2008) using the method based on Tononi’s information

integration theory that it could take up to  $10^{9000}$  years to complete a full analysis of a very limited 18,000 neuron network; and since the real brain has much more neurons, we are very unlikely to be able to model the entire human brain (in accordance with this theory) in the foreseeable future (Gamez, 2010).

Even though this is partly true, there is no other way around but to study and understand the architecture of the phenomenal world (and its biological constituents) of human beings (as having full-fledged phenomenal consciousness), if we wish to give such capacity to our robots (Fingelkurts et al., 2009a). We underline that machine consciousness could not be studied without considering phenomenal states. The same view has been developed by Aleksander (2009): "...those who use entirely functional methods rooted in AI must at least explain in what sense their models can be said to contain a phenomenal world, otherwise their work would not be considered as contributing to the aims of machine consciousness". From another side, the understanding of an immediately preceding level in the brain organization on which consciousness supervenes and to which it is isomorphic (Fingelkurts et al, 2009a,b; 2010b) is also important, if we aim to create an artificial system (robot) in which consciousness and thinking would *self-emerge*. Fortunately, current cognitive findings allow researchers to describe the hierarchy of the human phenomenal (conscious) world and related to it rational thinking in a way which could be integrated with accumulated brain activity data to form a unified and common framework that promises a plausible modeling perspective (Fingelkurts et al., 2010a).

Below we will illustrate the phenomenal world and rational thinking by describing the most important features which are required for instantiation of phenomenal consciousness and thinking.

## **2. Human Phenomenal Consciousness and Thinking**

It seems that conscious experiences (at least in humans) are intimately related to thoughts. For example Carruthers (2005) pointed: "What constitutes an experience as phenomenally conscious, in my view, is that it possesses a dual representational content: both world (or body) representing and experience representing. And experiences come to possess such a dual content by virtue of their availability to a higher-order thought faculty (which is capable of entertaining higher-order thoughts about those very experiences)". In other words, this world and body "presenting" is done via their higher-order analog contents – thoughts, which represent, and replicate in "seeming fashion", their first-order contents. Rosenthal (2005) who first introduced the higher-order thought theory of consciousness about 20 years ago also argues that we are immediately conscious of a conscious state because that awareness is part of the state itself. Therefore, according to him, having a (suitable)

higher-order thought is necessary and sufficient for there to be “something” that it is like for an organism to have any given sensory state (Rosenthal, 2008). Perhaps the whole problem was best expressed by René Descartes in his famous postulate: “I think, therefore I am” (Descartes, 1960/1637). This, however, does not mean that there cannot be some low, elemental forms of experience without a full-fledged rational thought (see below Section 2.1).

Implementing artificial consciousness thus may require the very notion of thinking to be considered at some level within the hierarchy of phenomenality. Until we can dissect the human phenomenal world along with related thinking and accurately describe the various elements that constitute them, we cannot expect to relate these to a functioning human brain. These requirements must be met in order to work out a plausible architecture for the creation of artificial consciousness and thought. Here, the concept of phenomenal consciousness refers to the world of subjective experiences (phenomena such as seeing, hearing, touching, feeling, embodiment, moving, and thinking) that happen to a person right at this moment (Fingelkurts et al., 2009a).

Now the question is: can we describe a possible functional architecture that might serve to realize the phenomenal world and conscious thinking, in the sense discussed above? The following Subsection is dedicated to this issue.

### *2.1. Architecture of the human phenomenal consciousness and related thinking*

Both, the phenomenal world and thinking (rational/goal-directed and spontaneous) could be implemented by a hierarchical modular architecture where there are basic phenomenal and cognitive *operations* that function as elementary building blocks of complex ones, which furthermore constitute phenomenal objects, images and thoughts.

Therefore, the fundamental notion that allows one to describe phenomenal consciousness and thinking under a common framework is that of *operation*. Formally “operation” stands for the *process* (or series of acts/functions) that applied to an operand, yield a transform, and is *limited in time* – it has a beginning and an end (Krippendorff’s Dictionary of Cybernetics, 1989; see also Burris and Sankappanavar, 1981); and can be broadly defined as the *state of being in effect* (Collins Essential English Dictionary, 2006). This definition provides a basis for discussing the relative *complexity* and *compositionality* of operations, where there is a more complex operation/operational act that subsumes the simpler ones (Fingelkurts and Fingelkurts, 2003, 2005; Fingelkurts et al., 2010a).

The lowest (first) level of discussed architecture is “constructed” from operations through which “phenomenal content”, made up of the raw data from the world as presented by the senses, is generated. These are so-called phenomenal features (qualities): the “stuff” that the experiences per se

are made of (Revonsuo, 2006). Further disassembling of these features would lead to the nonconscious biological level; therefore, these phenomenal features are the elemental entities of phenomenal architecture. It has been suggested that all phenomenal contents are embedded in a unifying spatial 3D coordinate system (phenomenal space) in order to be directly present in someone's subjective experience (Dainton, 2000; Metzinger, 2003; Revonsuo, 2006; Trehub, 2007). The psychology literature offers compelling evidence that such volumetric subjective space is readily available in the mind (Kosslyn, 1980; Shepard, 1982; Finke, 1989). So does our everyday subjective experience. It has been further proposed that this phenomenal space in which all experiences take place forms a bridge between nonconscious biological mechanisms and phenomenal consciousness (Revonsuo, 2006). For the overall study of thinking, these findings are relevant in two ways (von Müller, 2010): (1) they provide a description of the “logistical basement” of all thinking operations; and (2) they shed light on some general principles, such as “categorization”, that are based on massively iterated processes of separation and aggregation. Note that at this level the operation of categorization is expressed in its most primitive form (for example, it might be based on a threshold). Both of these processes are found again and again (with increasing vividness) on all subsequent layers of higher complexity in the hierarchy.

The second level refers to the processes that are still pre-lingual, but in which connecting operations are executed on mental contents. The basic first-level operation of categorization reappears on that second level in a most powerful way as a “pattern recognition”, and is joined by a second very basic operation – “comparison” (von Müller, 2010). In addition, at that level, there already exist early forms of intuitive assessment of causal relations, compatibility relations, and conditional relations. These operations form a basis for the fact that the experiential contents appearing in our conscious space (first level) are joined together into holistic entities of the highest order (this second level), something which Metzinger calls a global Gestalt (Metzinger, 1995). The formation of higher order operations is realized by *spatial* neighboring relations and especially by *temporal* identity within an experienced present, i.e. by subjective simultaneity, by being given within a single *psychological moment* of “now” (Metzinger, 2003; Marchetti, 2009). Any such holistic phenomenal object can be further organized into hierarchical parts (or features) of a more complex object, or on the contrary decomposed, where all of the components can be realized as separate simpler phenomenal objects independent of each other and with their own Gestalt and semantic windows (for similar views about mental objects see Fodor and Pylyshyn, 1988; van Leeuwen, 2007). As a consequence, this phenomenal level is characterized by enormous *multivariability* and *combinatorial* capacity capable of realizing an astronomical number of different phenomenal qualities, patterns, and objects of different complexity (Fingelkurts et al., 2009b, 2010a). This level is crucially relevant for the

understanding of human thinking because operations of this level continue to play a very influential role as underlying building blocks in all forms of higher level thinking processes. Additionally, it is at this level where another important feature of phenomenal space emerges – it is its centeredness, which is the spatial volume surrounding the “subjective self” and which is experienced as spreading outward in all directions from that virtual subjective self (Revonsuo, 2006; Metzinger, 2009). Such an egocentric reference frame or the first-person perspective was called perspectivalness: it possesses a focus of experience, a point of view (Metzinger, 1995).

The next (third) level of architecture deals with the appearance of higher-order reflective (or linguistic) thought which lies at the basis of human language. Indeed, if a “subject” appears, it seems unavoidable that he/she can assign him/herself some actions/activities and the consequences of his/her actions/activities (which is expressed linguistically by the “subject + verb” construction), or that the subject distinguishes him/herself from the object/other subjects (with all the ensuing forms of relations between them, which are linguistically expressed by conjunctions, prepositions, etc.) (Marchetti, 2010). This triggers an explosion of the variety and richness of cognitive operations (Benedetti, 2006; Marchetti, 2006). The reason for this explosion is that symbol-based language allows for much higher degrees of self-referential operations. Gaining the ability to produce symbolic “handles” for the products of lower level operations opens an almost infinite richness of conceptual (rational) thinking (von Müller, 2010). However, despite this enormous phenomenological richness of symbol-based thinking, it is possible to identify a number of basic operations of this level that function like a small library in the configuration of complex thoughts (Benedetti et al., 2010): (a) Operation of attentional focalization, (b) Operation of attentional discarding, (c) Operation of representation, (d) Operation of comparison, (e) Operation of presence keeping, and (f) Operation of memory.

The fourth and last level deals with the domain of highly complex reasoning architectures and the increasing specialization of the overall domain of cognitive processes (Perlovsky, 2006). Here the differentiation between strategic thinking (which is oriented towards goal-attainment), scientific thinking (which is explanation-oriented), artistic thinking (which focuses on articulating experiences) and philosophical thinking (which asks for sense and meaning) could be observed (von Müller, 2010). Additionally, characteristically different “thinking styles” as well as the emergence of thought patterns that go beyond the realm of experience, such as complex numbers and  $n$ -dimensional spaces are presented at this level.

Every part of this hierarchical phenomenal architecture is simultaneously present to every other part/component, creating a spatial co-presence (spatial and temporal coincidence) in the same and unified phenomenal world (Metzinger, 2003; Revonsuo, 2006; see also Baars, 1988). At the same

time, each part of this hierarchical phenomenal world is not monolithic; instead it has its own inherent fine structure. In this context every phenomenal pattern or object exists within every other more complex one; therefore these objects should not be considered as objects in a conventional sense (van Dijk, 2006). Rather, they should be seen as reciprocally entangled autopoietic machines (Maturana and Varela, 1980), i.e., self-creating processes, or dissipative structures (Nicolis and Prigogine, 1977) that are nevertheless relatively stable and thus could be conceived as distinct objects. Importantly, all these phenomenal patterns/objects/images/thoughts are transparent for us (we do not experience them as representations of external objects, scenes, or thoughts; instead we just perceive them right there present for us (for detailed and accurate conceptualization, see Metzinger, 2003 and Revonsuo, 2006; for an alternative view see Manzotti, 2006).

There is one property of phenomenal consciousness which is relevant for all levels of its hierarchy – it is the tendency to wonder, flitting from one phenomenal content/object/image/thought to the next with fluidity and ease (Singer, 1966; Mason et al., 2007; Bar et al., 2007; Christoff et al., 2008). James (1890) called this property a “stream of consciousness”, where phenomenal consciousness continually moves from one relatively stable part (content/object/image/though depending on the hierarchical level of phenomenal architecture) to another relatively stable part, and these stable parts are separated by abrupt transitive periods. Note that in the physical jargon such abrupt transitive periods are named critical points (Stanley, 1987) that mark the border between macroscopic determination and macroscopic indeterminacy (Bak et al., 1987; Antoniou et al, 2000).

## *2.2. Synthetic phenomenology and future direction*

Within last several years there have been attempts to artificially model or even implement some features of the phenomenal world in robotic systems. This emerging discipline has the name “Synthetic Phenomenology” (SP) (Gamez, 2010). One example of this type of research is Holland’s and Goodman’s (2003) robotic system Khepera which exhibits simple behavior and can produce a graphical representation of its own internal model using Linåker’s and Niklasson’s (2000) Adaptive Resource-Allocating Vector Quantizer method to build up concepts that correspond to a combination of sensory input and motor output. A similar approach to graphically represent the “imagination” of a Khepera robot was undertaken by Stening et al. (2005). Other related work in SP was carried out by Chrisley and Parthemore (2007), who used a SEER-3 robot to specify the non-conceptual (“phenomenal”) content that is difficult to express in natural language. Chella et al. (2005) are developing a CiceRobot which is largely based on perceptual “awareness” in vision where a



representation of what is expected (“imagined”) by the robot is compared with sensory visual data from the environment in order to lead to action.

The direction of this engineering approach can be interpreted as a *mimickry* of the inner (“phenomenal”) states based on some theory of consciousness or the limited set of its features. A quite similar path is taken by Sloman and Chrisley (2003) with their virtual machine functionalism. However, ignoring the brain constituents of consciousness will never allow modeling of the foundational principles of the phenomenal world and thus the creation of a true conscious robot. Following Revonsuo (2006) we stress that at the lower (in comparison with the phenomenal) level of brain organization there should be nonexperiential entities (some complex electrophysiological mechanisms) that function as the realization base of phenomenal space–time. Indeed, if phenomenal consciousness is a biological phenomenon within the confines of the brain, then there must be some specific level of organization and some specific spatial–temporal grain in the brain where consciousness resides. We underline that in order to create an artificial system (robot) in which consciousness and thinking would *self-emerge*, we need to model this *immediately preceding level* (thought it could be highly hierarchical) in the brain organization on which consciousness *supervenes* and to which it is *isomorphic* (Fingelkurts et al, 2009a,b, 2010b).

If the “levels” of phenomenal consciousness hierarchy, which we have described in the previous Subsection, really are separate levels of the overall spatial-temporal dynamics of a mind, then it should be possible to describe them by means of discrete classes of neural/brain operations. The discrete models are considerably easier to analyze, both mathematically and computationally, as well as to model. From a strictly engineering point of view, the neural substratum of a thought is not essential (Emiliani, 1990; Sloman and Chrisley, 2003; Sloman, 2004): what is essential for the presence of conscious thought is that there is a whatsoever substratum which implements the correct structure of operations (*operational level*) which take place in our brain during thinking (Fingelkurts et al., 2010b). In other words, it might be stated that thought is not only what happens in our brain: it is all which happens in any substratum which shares the functional architecture of our brain; or in all those substrata which share a formally equivalent *operational architecture* (Fingelkurts et al., 2009a, 2010b).

Therefore we need to reveal, study and objectively describe such brain functional architecture which allows realization of a mind and which is isomorphic to it. In this case there should be no objection to anyone venturing into the project of realizing this architecture artificially (Sanz, 2009; Gamez, 2009). In fact, when the description is sufficiently precise, complete and unambiguous, as it is in the case of formal algorithms, there are well-known standard tools (namely, programming systems and computers) for executing such a project (Havel, 1993). The need to create a working

model of single *integrated brain-mind architecture* can be expected to lead to a radically new brain-mind-inspired hardware architecture (Denham, 2002). However, to do so we would need first an appropriate theoretical and methodological (informal) framework. This framework should give researchers an idea how specific mental phenomena with measurable physical counterparts could fit into the unified brain-mind architecture, and pay attention to the philosophical problems of how these physical processes relate to the mental processes.

So, what should this theoretical-methodological framework look like in order to adequately support mental (phenomenal, psychological, linguistic, neuropsychological, neurolinguistic) phenomena and their neurophysiological underlying operations, as well as being plausible for the engineering purposes? We believe it should be an *operational* model, that is, a framework centered on the notion of “*operation*” (Fingelkurts and Fingelkurts, 2001, 2003, 2005; Fingelkurts et al., 2009b, 2010a) rather than attempting to directly mimic the intricate chemical and physiological mechanisms of the brain or functional states of the conscious mind.

### **3. Operational Architectonics of Brain-Mind Functioning**

In order to identify brain operations responsible for the production of higher-order mental phenomena such as thought and conscious processing, a conceptual-theoretical framework proposing what to look for and at which level to do so is necessary (Benedetti et al., 2010). To be adequate, this theoretical framework should be able to connect the phenomenal aspects of consciousness and their underlying brain operations, which basically constitute them. Using Revonsuo words (2006), one “should take very seriously both the subjective psychological reality of consciousness and the objective neurobiological reality” in their intimate connectedness within *a single and integrated continuum* (Fingelkurts et al., 2009b).

The notion of *operation*, then, is fundamental and central in bridging the gap between brain and mind: it is precisely by means of this notion that it is possible to identify what at the same time belongs to the phenomenal conscious level and to the neurophysiological level of brain activity organization, and mediates between them (Fingelkurts and Fingelkurts, 2003, 2005; Fingelkurts et al., 2009b, 2010a). Indeed, both, the material neurophysiological organization that characterizes the brain and the informational order that characterizes the mind necessarily involve such events as operations at their cores.

As we have stated in Section 2.1, “operation” is broadly defined as the process or state of being in effect and that it has the beginning and end (for further discussion, see Fingelkurts et al., 2010a). It should be stressed that this is so regardless of whether this process is

conceptual/mathematical/phenomenal or physical/biological/physiological. In fact, everything which can be represented by a *process* is an *operation*. Understanding of the operation as a *process* and considering its *combinatorial* nature, seems especially well suited for describing and studying the mechanisms of how information about the objective physical entities of the external world can be integrated, and how unified/coherent phenomenal objects or thoughts can be presented in the internal subjective world by means of entities of distributed neuronal brain assemblies. It is only at this level of integration (through functional isomorphism principle; Fingelkurts and Fingelkurts, 2001; Fingelkurts et al., 2009b) that we may hope to relate and bridge the gap between phenomenal level and empirical evidence of its brain operational implementation (Fingelkurts et al., 2010a).

### 3.1. The Operational Architectonics theory

The Operational Architectonics (OA) theory (Fingelkurts and Fingelkurts 2001, 2003, 2004, 2005, 2006, 2008; Fingelkurts et al., 2009b, 2010a,b) offers a neurobiologically plausible framework which states that whenever any pattern of phenomenality (including reflective thought) is instantiated, a corresponding and appropriate brain activity pattern is emerged<sup>1</sup> (Fingelkurts and Fingelkurts 2001, 2005; Fingelkurts et al., 2009b, 2010a). These brain activity patterns (expressed as the virtual operational modules) are brought into existence by joint operations of many functional and transient neuronal assemblies in the brain (Fingelkurts and Fingelkurts 2005, 2006; Fingelkurts et al., 2009b, 2010a). Transient neuronal assembly is defined as a set of neurons that cooperate (synchronize their activity) to perform a specific computation (operation) required for a specific task (Palm, 1990; Eichenbaum, 1993; von der Malsburg, 1999; Buzsáki, 2006). The question is: what might be the nature of these brain activity patterns (of appropriate kind), which would reflect or even instantiate the phenomenal world (considering that they should be as dynamic as phenomenal consciousness, have the same hierarchical complexity, be relatively independent from the neurophysiology, and be “well-defined” and “well-detected”)?

Our recent analysis (Fingelkurts et al., 2010a) shows that the nature of these patterns should refer to the coordinated behavior of local fields, generated by local transient neuronal assemblies and could be measured by means of electroencephalography (EEG) (Freeman, 1992). According to Freeman (1975, 1992), these local fields’ (mesoscopic) effects operate at a spatial scale of ~1 cm and temporal

---

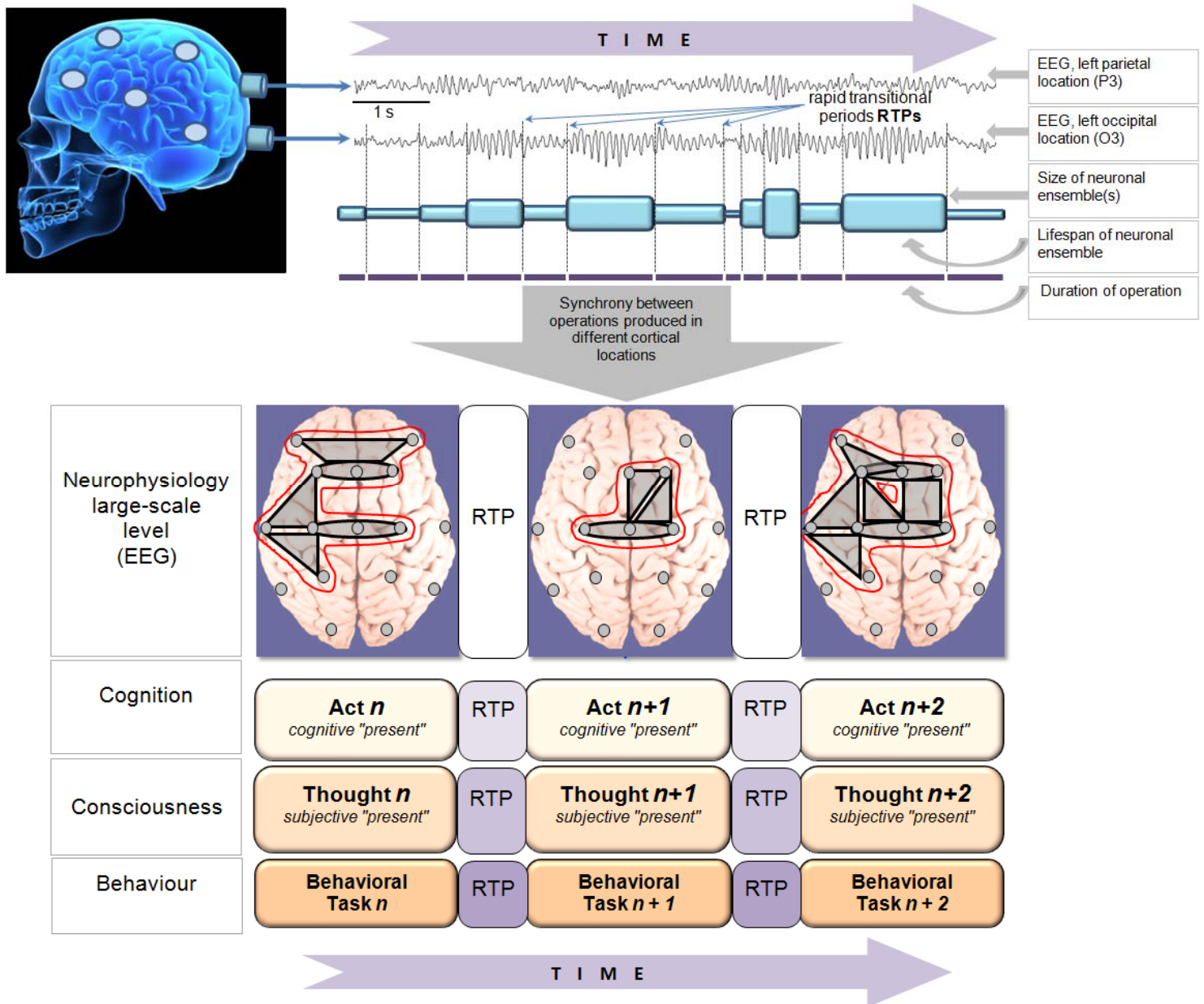
<sup>1</sup> Even though this framework has some similarities with other theoretical conceptualizations, it is quite distant from them in the core principles (for the detailed comparative analysis, see the last section in Fingelkurts and Fingelkurts, 2008). Additionally, besides numerous differences between the ways the different theoretical approaches are developed and in contrast to many other theories, the OA framework offers a range of methodological tools which enable in practice to measure the postulated entities of the theory (Fingelkurts and Fingelkurts, 2008).

scale of ~100 ms and, thus, mediate between the two extremes of cortex organization: single neurons and the major lobes of the forebrain. In this context the OA theory explores the temporal structure of information flow and the inter-area interactions within a network of dynamical, transient, and functional neuronal assemblies (whose activity is “hidden” in the complex nonstationary structure of local EEG signals; Kaplan, 1998; Kaplan et al., 2005) by examining topographic sharp transition processes (on the millisecond scale) in the local EEG fields<sup>2</sup> (Fig. 1; see also Fingelkurts and Fingelkurts, 2001, 2004, 2005, 2006, 2008). Detailed analysis of the complex structure and hierarchical architecture of EEG fields (see the following Subsections) reveals the existence of a particular operational space-time (OST) which literally resides within the brain internal physical space-time (IPST) and is functionally isomorphic to the phenomenal space-time (PST).

As we have proposed elsewhere (Fingelkurts et al., 2010a), OST constitutes the neurophysiological basis of mind phenomenal architecture (PST). Precisely, the operational (OST) level of brain organization *intervenes between* internal physical brain architecture (IPST) on one side, where it literally resides, and experiential/subjective phenomenal structure of the mind (PST), to which it is isomorphic, on the other side. In other words, the physical brain produces a highly structured and dynamic electromagnetic field with *emergent* properties realized in the form of OST level; phenomenal (PST) level *supervenes* on the operational level with one-to-one correspondence and ontologically it is inseparable from this operational level (Fingelkurts et al., 2010b). However the phenomenal level is separable from the brain neuroanatomical processes. This point of view coincides with the engineering logic which states that the concrete neuronal substratum of a consciousness is not essential for its natural or artificial implementation (Emiliani, 1990; Sloman and Chrisley, 2003; Sloman, 2004). Thus, the operational level ties these two (neurophysiological and subjective) domains ontologically together through the shared notion of operation (Fingelkurts and Fingelkurts, 2003, Fingelkurts et al., 2009b).

---

<sup>2</sup> These EEG phenomena are rarely exploited due to the lack of analytical tools and methodology. Special techniques (which take into consideration the inherent quasi-stationary nature and structure of an EEG signal) are required for their detection. One may suppose that the local EEG fields’ segmentation described here is identical or similar to Lehmann’s technique for the momentary whole-brain electric field segmentation (Lehmann et al., 1987). This is not the case. The OA methodology is similar to the microstates method of Lehmann and colleagues only at the most abstract conceptual level. This similarity concerns only the assumption that the brain activity progresses not in a continuous manner, but is a succession of the microstates with abrupt changes in-between. The rest is different. Since the differences are discussed in detail in Fingelkurts et al., 2010a (footnote 71), here we stress only one aspect, which is important for the theme of the current article. In contrast to Lehmann’s whole-brain electric field microstates, operational modules (OMs) from the OA methodology have very rich internal structure, where the temporal information of each cortical area (which participates in the OM) is precisely known and preserved; additionally such OMs can be formed within any frequency band and even between different frequency oscillations.



**Figure 1. Schematic illustration of the neuronal assembly's dynamics and its relation to an operation and to a large-scale neurophysiological level of operational modules (OMs).** As an example, the simplest case is shown, when cognitive, phenomenal and behavioral operations/acts coincide in time (in most cases these relations are more complex). Cognitive, phenomenal, and behavioral levels illustrate the ever-changing stream of cognitive/phenomenal/behavioral acts, where each momentarily stable pattern is a particular cognitive/phenomenal/behavioral macro-operation. Thus, the stream of cognitive/phenomenal/behavioral experience has a composite structure: It contains stable nuclei (or operations/thoughts/images/acts) and transitive fringes (or rapid transitional periods; RTPs). At the EEG level these processes are reflected in the chain of periods of short-term metastable states (or OMs) of the whole brain and its individual subsystems (grey shapes), when the numbers of degrees of freedom of the neuronal assemblies are maximally decreased, due to synchronized operations. Grey shapes illustrate individual OMs. Red line illustrates complex OMs. Changes from one complex OM to another are achieved through RTPs.

### 3.1.1. *The low level of brain-mind Operational Architectonics*

As it has been discussed in our previous work (Fingelkurts et al., 2009b; 2010a), local EEG waves recorded from the scalp are the result of self-organized integrated excitatory and inhibitory post-synaptic potentials of neuronal membranes. Since they reflect extracellular currents caused by synchronized neural activity within the local brain volume (John, 2002; Freeman, 2007), they are expressed within local EEG signals in the form of quasi-stationary segments, each of which represent an envelope of amplitude modulation (so called a “common mode” or a “wave packet”; Freeman and Vitiello, 2006) in the neuronal mass under the recording electrodes. These EEG quasi-stationary segments are “glued” to each other by means of the rapid transitional processes/periods (RTPs) (Fig. 1; Fingelkurts and Fingelkurts, 2001, 2008; Kaplan et al., 2005). In the physics literature RTPs are referred to as renewal (or critical) events; namely, the events that reset the memory of the system so that waiting times between two such events are all mutually independent, as proved by Allegrini et al. (2009). This latter property is in fact a mathematical definition of the well-known in physics phenomenon of “intermittency”, and is in fact compatible with self-organized criticality in physical systems (Bak et al., 1987) and in the brain (Novikov et al., 1997; Linkenkaer-Hansen et al., 2001; Buiatti et al., 2007; Plenz and Thiagarjan, 2007; Chialvo, 2008; Gong and van Leeuwen, 2009; Werner, 2009).

The neurons are physical entities in the brain and their activity does not correlate reliably with cognition and levels of consciousness (for a review see Fingelkurts et al., 2010a). Therefore the whole neuronal net (together with axon terminals, dendrites and glial cells) corresponds to the non-phenomenal realm. On the contrary, the spatially and temporally structured electromagnetic field (McFadden, 2002) produced by the functional and transient neuronal assemblies is an appropriate candidate for the entity within which all operational and isomorphic (to them) phenomenal contents (including “self”) can be presented (Fingelkurts et al., 2010a,b). Therefore the local fields of transient functional neuronal assemblies are equivalent to operations which can be conscious (phenomenal).

Simple brain-mind operations are reflected at the EEG level in the quasi-stationary segments, which are, in a way, standing waves within a 3D volume (Nunez and Srinivasan, 2006). It has been shown experimentally that these EEG segments are reliably and consistently correlated with changes in the phenomenal (subjective) content during both spontaneous (stimulus independent) and induced (stimulus dependent) experimental conditions (for the review see Fingelkurts and Fingelkurts, 2008). Moreover, it has been documented that different neuronal assemblies’ local fields are correlated with different conscious percepts (Freeman, 2007; Singer, 2001) and that if cognitive processing does not take place, these specific transient neuronal assemblies do not appear (Pulvermueller et al., 1994).

Additionally, it was shown that these local fields (indexed by EEG segments), through the process of operational synchrony, can create an even more complex repertoire of volumetric spatial-temporal patterns, that subdivide the electromagnetic volumetric space of the brain into periodic alternating partitions (we will return to the discussion of these complex patterns in the next Subsection). Thus, we may conclude that the totality of local and transient (dynamic) electromagnetic fields corresponding to operations which instantiate self-presenting, qualitative features can help us to explain the next higher level of phenomenal organization in the brain.

### 3.1.2. *The high level of brain-mind Operational Architectonics*

To have an experience of any complex phenomenal object or thought, several features of that object or thought should be spatially and temporally integrated (Treisman and Gelade, 1980; Blake and Yang, 1997; Cleeremans, 2002). In agreement with the above description, we already know that different phenomenal features are presented in the brain by local fields/operations generated by different transient neuronal assemblies. Temporal synchronization of these local fields/operations (Fig. 1) produces *complex* brain operations (Fingelkurts and Fingelkurts, 2001, 2003; Fingelkurts et al., 2009b, 2010a). Therefore, through the generation of temporal correlations, many spatially scattered neural operations (events) can be integrated into a higher-order whole (an object or thought) appearing in the time-window of “present” (Metzinger, 1995; van Leeuwen, 2007). Thus, *many events* become *one object* (Fig. 1). As a result, metastable brain states emerge to accompany the realization of such brain complex operations, where each of them is instantiated by the volumetric spatial-temporal pattern in the electromagnetic field (Fingelkurts and Fingelkurts, 2001, 2004; Fingelkurts et al., 2010a). We call these *metastable* spatially and temporally organized patterns in the electromagnetic field Operational Modules (OM) (Fingelkurts and Fingelkurts, 2001, 2003). The OMs are metastable because of intrinsic differences in the activity between neuronal assemblies, which constitute OMs, each doing its own job, while at the same time still retaining a tendency to be coordinated together within the same OM. It is exactly this simultaneous existence of autonomous and integrated tendencies which signifies the metastable principle of brain functioning (Kelso, 1991; Kelso et al., 1990; Bressler and Kelso, 2001; Fingelkurts and Fingelkurts, 2004).

Based on experimental findings we have further suggested that these OMs constitute a higher level of abstractness (Fingelkurts et al., 2009b; Fingelkurts and Fingelkurts, 2005, 2006), because these OMs are relatively independent from the neurophysiological processes in the brain. They are independent from intrinsic brain anatomical topology that determines which single neuron of a given

anatomical circuit produces a particular spike pattern of a given temporal signature (for similar argumentation, see Köhler and Held, 1947; McFadden, 2002; Dresch-Langley and Durup, 2009).

At the EEG level, the constancy and continuous existence of spatial-temporal OMs persist across a sequence of discrete and concatenated segments of stabilized (synchronized) local EEG activities that constitute them (Fig. 1). It has been shown experimentally that the sequences of segments between different local EEG signals are indeed synchronized to a certain extent and form short-term metastable topological combinations (OM), with different sizes (number of cortical locations involved) and life-spans (temporal duration) (Kaplan and Shishkin, 2000; Fingelkurts et al., 2003a,b, 2004a,b). We argue that at the phenomenological level, the lasting OM would be experienced as a “phenomenal present” of consciousness. Different durations of time-windows expressed in the life-span of OMs could realize different “grains” or different resolutions by means of which various entities can be presented subjectively.

Our research has shown that OMs (being by themselves the result of synchronized operations produced by distributed transient neuronal assemblies) could be further operationally synchronized between each other at different time scale, and thus forming a more abstract and more complex OM, which would constitute the new integrated experience (Fingelkurts and Fingelkurts, 2003, 2005, 2006). However, the higher-order OMs (embedding of mental content) presuppose that bound simpler OMs are superimposed without loss of any relevant information. We have proposed that each of the complex OMs is not just a sum of simpler OMs, but rather a natural union of abstractions about simpler OMs (Fingelkurts and Fingelkurts, 2003, 2005, 2006). Therefore, OMs have a rich *combinatorial complexity* and the ability to reconfigure themselves rapidly, which is crucially important for the subjective presentation of highly dynamic phenomenal experiences (Section 2; see also Fig. 1). Yet the opposite process is also possible, where complex OMs could be decomposed to simpler ones all the way down to the basic operations. Such decomposition would be responsible for a segmentation of our subjective experience and focused conscious states (Dainton, 2000; Revonsuo, 2006).

Some physicists tend to interpret OMs within the theory of avalanches (explained in detail in Zapperi et al., 1995; Beggs and Plenz, 2003, 2004; Plenz and Thiagarjan, 2007). Avalanche is defined as a spontaneous and abrupt burst of activity observed on variable numbers of electrodes for different periods of time separated by the silent or quasi-stable periods (Beggs, 2007). Recently Allegrini and coworkers reported in a series of publications that OMs (defined as the temporal RTP coincidences among different EEG channels) are the real source of 1/f signal in the brain and that OMs are indeed driven by a renewal process with power index  $\mu \approx 2$  (Allegrini et al., 2009; 2010a,b), which is in line with Beggs and Plenz’s (2003) avalanche research. In physics the value  $\mu=2$  indicates a transition



between two kinds of ergodicity breakdown, stationary and nonstationary, respectively (Lee, 2007; Silvestri et al., 2009). Moreover, it has been shown that complex networks at  $\mu \approx 2$  realize the optimized condition for transmitting and receiving information (West et al., 2008). This condition is also obeyed by human language (Allegrini and Grigolini, 2004) and by music (Bianco et al., 2007). Such correspondences look like an interesting topic that could be explored more fully in future studies. Some of these and other broader contexts of OA theory and conceptual relations were discussed in several previous publications (Fingelkurts and Fingelkurts, 2004, 2005; Fingelkurts et al., 2009b, 2010a; see also Werner, 2007; Freeman, 2010) to which we refer the interested reader.

### *3.1.3. Dynamic aspect of brain-mind Operational Architectonics*

Freeman (2007) states: “the stream of consciousness is cinematographic rather than continuous, with multiple frames in coalescing rivulets”. Indeed, our every day first-person experience clearly shows that the actualization of full-fledged phenomenal objects or higher-order thoughts is realized on a “one-at-a-time” basis, moving serially from one phenomenal pattern to another (Dainton, 2000; Revonsuo, 2006; Bar et al., 2007). This process gives rise to a stream of consciousness/thoughts (James, 1890).

According to OA theory, the succession of phenomenal images or thoughts is presented by the succession of discrete and relatively stable OMs, which are separated by rapid transitive processes, i.e. abrupt changes of OMs (Fig. 1). It has been shown experimentally that at the critical point of transition in mental state e.g. during changes of phases in memory or other cognitive task (Fingelkurts, 1998; Fingelkurts et al., 2000, 2003a), the OM undergoes a profound reconfiguration which is expressed through the following process: a set of local bioelectrical fields (which constitute an OM), produced by transient neuronal assemblies located in several brain areas, rapidly loses functional couplings with one another and establishes new couplings within another set of local bioelectrical fields (brain cortical areas); thus demarcating a new OM in the volumetric OST continuum of the brain (Fig.1 ). In this context the subjective persistence of a phenomenal object, scene or thought depends on the stability of the brain’s OM dynamics. Some of them persist longer than others because the operational relations underlying an OM are more stable. Recent studies indicate that during passive rest cortical areas more prone to be recruited into OMs have a complexity index similar to the index of the global brain intermittent process (Allegrini et al., 2010b). In particular these areas are those located in the midline region, collecting electric signals from the two hemispheres. Authors interpret their data as an indication that the brain is working in a critical condition (Allegrini et al., 2010a).

Furthermore, it has been shown that there are multiple, simultaneously occurring interactions between different cognitive operations, which are subserved by the simultaneous presence of transient neuronal assemblies as autonomous entities (Gong and van Leeuwen, 2009) and OMs (synchronized neuronal assemblies) of different complexity (Fingelkurts et al., 2000, 2003a). Because of the composite polyphonic character of the electrical brain field (EEG), this field can be presented as a mixture of many time-scale processes (Nunez, 2000; Basar et al., 2001). Consequently, a large number of functionally distinct OMs can co-exist simultaneously on different time-scales and even between them (for experimental support, see Fingelkurts, 1998; Kaplan and Shishkin, 2000; Fingelkurts, et al., 2004a,b). Hence, in this perspective, the immediately needed complex cognitive or mental operation within a particular time-scale can be presented by immediately emerged specific OM on the same time-scale without the need to disassemble the other OM which exists on a different time-scale (Fingelkurts et al., 2003; see also Fingelkurts et al., 2009b; 2010a). This mechanism allows the brain to present multiple multimodal stimulus, objects, actions and/or thoughts by distant functional OMs. Functional coupling of many OMs on a particular but common time-scale would assign many phenomenal objects/images/thoughts to a present moment “now” and would guarantee the integrated phenomenal world-model postulated by Dainton (2000), Metzinger (2003) and Revonsuo (2006).

#### 4. Concluding Remarks

The Operational Architectonics (OA) hierarchical framework of brain and mind functioning outlined here proposes a change of strategy in current machine consciousness robotics. Instead of using the low-level neurophysiology mimicking (Markram, 2006), high-level features of consciousness mimicking and exploratory programming (for a discussion see Holland, 2003b) methods that are common in the field, the *brain-mind unified* OA model proposes one more conceptual-theoretical framework to the range of possible scenarios to consider for the model-driven engineering. This unified theoretical OA model of brain-mind functioning explicitly captures the basic essence of brain functional architecture that does, indeed, constitute a theory of consciousness in its own right (Fingelkurts et al., 2010a): (a) it takes into account what phenomenal consciousness feels like from the *first-person perspective*; (b) it considers the *compositionality* of phenomenal objects and thoughts; (c) it captures the *stream of thoughts*; (d) it also depicts the *relations* between consciousness, brain and external physical world in a scientifically plausible way; and (e) it gives special importance to the principle of “*operation*” which is an important notion both for the functioning of the brain and mind as well as for the artificially engineered systems.

In contrast to many theoretical approaches (with which the OA has some similarity), the OA framework offers a range of methodological tools which enable researchers to measure the postulated entities of the theory in practice (Fingelkurts and Fingelkurts, 2008). For example, the specific tools of EEG analysis (Fingelkurts and Fingelkurts, 2001, 2008) are especially suited for studies of nonstationary signals and uniquely capable of investigating the dynamic and metastable changes of brain spatial-temporal patterns that are isomorphic with the phenomenal level. These tools essentially take into account repetitions of spatial-temporal patterns at all structural levels, thus capturing both dynamic as well as hierarchical complexities of brain activity which is nested within a multi-scale operational architecture (Fig. 1). The whole methodology allows the reconstruction of spatial-temporal patterns of phenomenal level directly from EEG data through isomorphic (to them) OMs of different complexity. Thus, in fact, the OA model allows researchers *to explore phenomenal architecture of the mind (PST) by measuring the brain operational space-time (OST) architectonics* (Fingelkurts et al., 2010a).

In this context the problem of producing man-made “machine” consciousness and “artificial” thought is the problem of duplicating all levels of operational architectonics hierarchy (with its inherent rules and mechanisms) found in the EEG field, which can constitute the neurophysiological basis of phenomenal level of brain organization (Fingelkurts et al., 2009a). The aim should be to abstract and formalize the principles of the hierarchy of operations which constitute phenomenal consciousness and thought, rather than attempting to directly mimic the whole diversity of chemical and physiological mechanisms of brain functioning or the whole diversity of consciousness’ states, which is a quite unrealistic enterprise (Koch and Tononi, 2008). In this case one could expect that by reproducing the one architecture (brain operational) we can observe the *self-emergence* of the other (mind phenomenal). However, the task of formalizing and mathematically analyzing the hierarchical OA model provides, as noticed by Denham (2002) a formidable challenge to mathematics and theoretical computer science and is likely to require the development of new mathematical conceptualizations and analysis methods (see also Freeman, 1999; Sloman and Chrisley, 2003; Haikonen, 2003).

As we have mentioned before (Fingelkurts et al., 2009a) whether the OA framework can provide a sufficient underpinning for machine phenomenology remains to be shown; however, the first attempt to model the self-organized distributed computing system based directly on the OA theory shows that such a system is superior than a centralized decision making algorithm (Burmakin et al., 2009). As we pursue our investigations we can expect to reveal and describe in more detail the complexity of the OA level of brain organization that could provide the basis for the brain-mind-

inspired architecture modeling. One day, if successful, it might be added to a machine (robot) to produce a human-like consciousness and thought.

## Acknowledgments

All authors contributed equally to this article. The authors would like to thank Giorgio Marchetti and three anonymous reviewers who provided thoughtful comments and constructive criticism. Special thanks for English editing to Dmitry Skarin. This work was supported by BM-Science Centre, Finland.

## REFERENCES

- Adami, C., 2006. What do robots dreams of? *Science* 314, 1093-1094.
- Allegrini, P., Grigolini, P., 2004. Intermittency and scale-free networks: a dynamical model for human language complexity. *Chaos Solitons Fractals* 20, 95-105.
- Allegrini, P., Menicucci, D., Bedini, R., Fronzoni, L., Gemignani, A., Grigolini, P., West, B.J., Paradisi, P., 2009. Spontaneous brain activity as a source of ideal  $1/f$  noise. *Phys. Rev. E Stat. Nonlin. Soft Matter Phys.* 80, 061914.
- Allegrini, P., Menicucci, D., Bedini, R., Gemignani, A., Paradisi, P., 2010a. Complex intermittency blurred by noise: Theory and application to neural dynamics. *Phys. Rev. Stat. Nonlin. Soft Matter Phys. E* 82, 015103.
- Allegrini, P., Paradisi, P., Menicucci, D., Gemignani, A., 2010b. Fractal complexity in spontaneous EEG metastable state transitions: new vistas on integrated neural dynamics. *Front. Physiol.* 1, 128.
- Aleksander, I., 2001. The Self 'out there'. *Nature* 413, 23.
- Aleksander, I., 2009. Designing conscious systems. *Cogn. Comput.* 1, 22–28.
- Angel, L., 1989. *How to Build a Conscious Machine*, Westview Press, Boulder, CO.
- Antoniou, N.G., Contoyiannis, Y.F., Diakonou, F.K., 2000. Fractal geometry of critical systems. *Phys. Rev. E Stat. Phys. Plasmas Fluids Relat. Interdiscip. Topics.* 62, 3125-3134.
- Arrabales, R., Ledezma, A., Sanchis, A., 2009. CERA-CRANIUM: A test bed for machine consciousness research. International Workshop on Machine Consciousness, Hong Kong, 14th June.
- Baars, B., 1988. *A Cognitive Theory of Consciousness*. Cambridge University Press, Cambridge.
- Baars, B., 1997. In *The Theater of Consciousness: The Workspace of the Mind*. Oxford University Press, New York.
- Bak, P., Tang, C., Wiesenfeld, K., 1987. Self-organized criticality: an explanation of the  $1/f$  noise. *Phys. Rev. Lett.* 59, 381–384.
- Basar, E., Basar-Eroglu, C., Karakas, S., Schurmann, M., 2001. Gamma, alpha, delta, and theta oscillations govern cognitive processes. *J. Psychophysiol.* 39, 241–248.
- Bar, M., Aminoff, E., Mason, M., Fenske, M., 2007. The units of thought. *Hippocampus* 17, 420–428.
- Beggs, J.M., 2007. Neuronal avalanche. *Scholarpedia*, 2(1), 1344.
- Beggs, J.M., Plenz, D., 2003. Neuronal avalanches in neocortical circuits. *J. Neurosci.* 23, 11167–11177.
- Beggs, J.M., Plenz, D., 2004. Neuronal avalanches are diverse and precise activity patterns that are stable for many hours in cortical slice cultures. *J. Neurosci.* 24, 5216–5229.
- Benedetti, G., 2006. Operational Noology as a new methodology for the study of thought and language: theoretical aspects and possible practical applications. *Cogn. Process.* 7, 217-243.
- Benedetti, G., Marchetti, G., Fingelkurts, A.I.A., Fingelkurts, A.N.A., 2010. Mind operational semantics and brain operational architectonics: A putative correspondence. *Open Neuroimag. J.* 4, 53-69.
- Bianco, S., Ignaccolo, M., Rider, M.S., Ross, M.J., Winsor, P., Grigolini, P., 2007. Brain, music, and non-Poisson renewal processes. *Phys. Rev. E* 75, 061911.
- Blake, R., Yang, Y. 1997. Spatial and temporal coherence in perceptual binding. *Proc. Natl. Acad. Sci. USA.* 94, 7115–7119.
- Bressler, S.L., Kelso, J.A.S., 2001. Cortical coordination dynamics and cognition. *Trends Cogn. Sci.* 5, 26–36.
- Buiatti, M., Papo, D., Baudonnière, P.-M., van Vreeswijk, C., 2007. Feedback modulates the temporal scale-free dynamics of brain electrical activity in a hypothesis testing task. *Neuroscience* 146, 1400–1412.
- Burrus, S.N., Sankappanavar, H.P., 1981. *A Course in Universal Algebra*. Springer-Verlag, New York.

- Burmakin, E., Fingelkurts, A.I.A., Fingelkurts, An.A., 2009. Self-organization of dynamic distributed computational systems applying principles of integrative activity of brain neuronal assemblies. *Algorithms* 2, 247-258.
- Buzsáki, G., 2006. *Rhythms of the Brain*. Oxford University Press, Oxford.
- Carruthers, P., 2005. *Consciousness: Essays from a Higher-Order Perspective*. Oxford University Press, New York.
- Chan, V., Liu, S.C., van Schaik, A., 2006. AER EAR: a matched silicon cochlea pair with address event representation interface. *IEEE Trans. Circuit. Syst. I* 54, 48–59.
- Chella, A., Frixione, M., Gaglio, S., 2005. Planning by imagination in CiceRobot, a robot for museum tours. In *Proceedings of the AISB symposium on next generation approaches to machine consciousness: imagination, development, intersubjectivity, and embodiment*, pp. 40–49.
- Chella, A., Manzotti, R., 2007. *Artificial consciousness*. Imprint Academic, Exeter.
- Chialvo, D.R., 2008. Emergent complexity: what uphill analysis or downhill invention cannot do. *New Ideas Psychol.* 26, 158–173.
- Chicca, E., Whatley, A.M., Dante, V., Lichtsteiner, P., Delbruck, T., Del Giudice, P., Douglas, R.J., Indiveri, G., 2007. A multi-chip pulse-based neuromorphic infrastructure and its application to a model of orientation selectivity. *IEEE Trans. Circuit. Syst. I* 5, 981–993.
- Chrisley, R.J., Parthemore, P., 2007. Synthetic phenomenology: Exploiting embodiment to specify the non-conceptual content of visual experience. *J. Conscious. Stud.* 14, 44–58.
- Christoff, K., Gordon, A., Smith, R., 2008. The role of spontaneous thought in human cognition. In: *Neuroscience of Decision Making*. O. Vartanian, D.R. Mandel, eds. Psychology Press, Philadelphia.
- Cleeremans, A., 2002. *The Unity of Consciousness: Binding, Integration, Dissociation*. Oxford Univ. Press, Oxford.
- Collins essential English dictionary, 2006. 2nd ed. Harper Collins Publishers.
- Dainton, B., 2000. *Stream of Consciousness*. Routledge, London.
- Denham, M., 2002. The architecture of brain and mind: Integrating low-level neuronal brain processes with high-level cognitive behaviours. The UKCRC Grand Challenges Workshop, Edinburgh, November.
- Descartes, R., 1960 (original 1637). *Discourse on Method and Meditations* (Laurence, J.L., translation). The Liberal Arts Press, New York.
- Dresp-Langley, B., Durup, J., 2009. A plastic temporal brain code for conscious state generation. *Neural Plast.* 2009, 482696.
- Eichenbaum, H., 1993. Thinking about brain cell assemblies. *Science* 261, 993-994.
- Emiliani, A., 1990. The order of thought: Wittgenstein on artificial intelligence and brain-processes. *Daimon. Rev. Filos.* 2, 125-138.
- Fingelkurts, An.A., 1998. Time-spatial organization of human EEG segment's structure. PhD Dissertation. Moscow State University, Moscow, (in Russian).
- Fingelkurts, An.A., Fingelkurts, A.I.A., 2001. Operational architectonics of the human brain biopotential field: Towards solving the mind-brain problem. *Brain Mind* 2, 261-296. Available from: <http://www.bm-science.com/team/art18.pdf>
- Fingelkurts, An.A., Fingelkurts, A.I.A., 2003. Operational architectonics of perception and cognition: A principle of self-organized metastable brain states. VI Parmenides Workshop, April 5–10, Elba/Italy. Available from: <http://www.bm-science.com/team/art24.pdf>
- Fingelkurts, An.A., Fingelkurts, A.I.A., 2004. Making complexity simpler: Multivariability and metastability in the brain. *Int. J. Neurosci.* 114, 843–862.
- Fingelkurts, An.A., Fingelkurts, A.I.A., 2005. Mapping of brain operational architectonics. In: *Focus on Brain Mapping Research*. F.J. Chen, ed. Nova Science Publishers Inc, New York, pp. 59-98. Available from: <http://www.bm-science.com/team/chapt3.pdf>
- Fingelkurts, An.A., Fingelkurts, A.I.A., 2006. Timing in cognition and EEG brain dynamics: discreteness versus continuity. *Cogn. Process.* 7, 135–162.
- Fingelkurts, An.A., Fingelkurts, A.I.A., 2008. Brain-mind Operational Architectonics imaging: technical and methodological aspects. *Open Neuroimag. J.* 2, 73-93.
- Fingelkurts, An.A., Fingelkurts, A.I.A., Neves, C.F.H., 2009a. Brain and mind operational architectonics and man-made “machine” consciousness. *Cogn. Process.* 10, 105–111.
- Fingelkurts, An.A., Fingelkurts, A.I.A., Neves, C.F.H., 2009b. Phenomenological architecture of a mind and operational architectonics of the brain: The unified metastable continuum. *New Math. Nat. Comput.* 5, 221–244.
- Fingelkurts, An.A., Fingelkurts, A.I.A., Neves, C.F.H., 2010a. Natural world physical, brain operational, and mind phenomenal space-time. *Phys. Life Rev.* 7, 195–249.
- Fingelkurts, An.A., Fingelkurts, A.I.A., Neves, C.F.H., 2010b. Emergentist monism, biological realism, operations and brain–mind problem. *Phys. Life. Rev.* 7, 264–268.
- Fingelkurts, An.A., Fingelkurts, A.I.A., Borisov, S.V., Ivashko, R.M., Kaplan, A.Ya., 2000. Spatial structures of human multichannel EEG quasi-stationary segments during memory task. *Vestn. Moskovsk. Univer. (Moscow State University Bulletin), Series 16, Biology* 3, 3–10, (in Russian).

- Fingelkurts, An.A., Fingelkurts, Al.A., Krause, C.M., Kaplan, A.Ya., Borisov, S.V., Sams, M., 2003a. Structural (operational) synchrony of EEG alpha activity during an auditory memory task. *NeuroImage* 20, 529–542.
- Fingelkurts, An.A., Fingelkurts, Al.A., Krause, C.M., Möttönen, R., Sams, M., 2003b. Cortical operational synchrony during audio-visual speech integration. *Brain Language* 85, 297–312.
- Fingelkurts, An.A., Fingelkurts, Al.A., Kivisaari, R., Pekkonen, E., Ilmoniemi, R.J., Kähkönen, S.A., 2004a. Local and remote functional connectivity of neocortex under the inhibition influence. *NeuroImage* 22, 1390-1406.
- Fingelkurts, An.A., Fingelkurts, Al.A., Kivisaari, R., Pekkonen, E., Ilmoniemi, R.J., Kähkönen, S.A., 2004b. Enhancement of GABA-related signalling is associated with increase of functional connectivity in human cortex. *Hum. Brain Mapp.* 22, 27–39.
- Finke, R.A., 1989. *Principles of Mental Imagery*. MIT Press, Cambridge.
- Fodor, J.A., Pylyshyn, Z.W., 1988. Connectionism and cognitive architecture: A critical analysis. *Cognition* 28, 3-71.
- Freeman, W.J., 1975. *Mass Action in the Nervous System*. Academic Press, New York.
- Freeman, W.J., 1992. Tutorial on neurobiology: From single neurons to brain chaos. *Int. J. Bifurcat. Chaos* 2, 451–482.
- Freeman, W.J., 1999. *How Brains Make up Their Minds*. Phoenix, London.
- Freeman, W.J., 2007. Indirect biological measures of consciousness from field studies of brains as dynamical systems. *Neural Netw.* 20, 1021–1031.
- Freeman, W.J., 2010. The use of codes to connect mental and material aspects of brain function: comment on: "Natural world physical, brain operational, and mind phenomenal space-time" by A.A. Fingelkurts, A.A. Fingelkurts and C.F.H. Neves. *Phys. Life Rev.* 7, 260-261.
- Freeman, W.J., Vitiello, G., 2006. Nonlinear brain dynamics as macroscopic manifestation of underlying many-body field dynamics. *Phys. Life Rev.* 3, 93–118.
- Gamez, D., 2008. *The development and analysis of conscious machines*. Unpublished PhD Thesis, University of Essex, UK.
- Gamez, D., 2009. The potential for consciousness of artificial systems. *Int. J. Mach. Consci.* 1, 213-223.
- Gamez, D., 2010. Information integration based predictions about the conscious states of a spiking neural network. *Conscious. Cogn.* 19, 294–310.
- Gong, P., van Leeuwen, C., 2009. Distributed dynamical computation in neural circuits with propagating coherent activity patterns. *PLoS Comput. Biol.* 5(12), e1000611.
- Haikonen, P., 2003. *The Cognitive Approach to Conscious Machines*. Imprint Academic, Exeter.
- Havel, I.M., 1993. Artificial thought and emergent mind. *Proceedings of the Thirteenth International Joint Conference on Artificial Intelligence Vol 1*, pp. 758-766.
- Holland, O., 2003a. Editorial introduction. *J. Conscious. Stud.* 10, 1–6.
- Holland, O., 2003b. *Machine consciousness*. Imprint Academic, Exeter.
- Holland, O., Goodman, R., 2003. Robots with internal models. In: *Machine consciousness*. O. Holland, ed. Machine consciousness. Imprint Academic, Exeter.
- Husserl, E., 1973 (original 1901). *Logical investigations* (Findlay, J.N., translation). Routledge, London.
- Indiveri, G., Chicca, E., Douglas, R. 2006. A VLSI array of low-power spiking neurons and bistable synapses with spike-timing dependent plasticity. *IEEE Trans. Neural Netw.* 17, 211–221.
- Jame, W., 1890. *The Principles of Psychology*, Vol I. Dover, New York.
- John, E.R., 2002. The neurophysics of consciousness. *Brain Res. Brain Res. Rev.* 39, 1-28.
- Kaplan, A.Ya., 1998. Nonstationary EEG: Methodological and experimental analysis. *Usp. Fiziol. Nauk (Success in Physiological Sciences)* 29, 35-55, (in Russian).
- Kaplan, A.Ya., Shishkin, S.L., 2000. Application of the change-point analysis to the investigation of the brain's electrical activity. In: *Nonparametric Statistical Diagnosis: Problems and Methods*. B.E. Brodsky, B.S. Darkhovsky, eds. Kluwer, Dordrecht, pp. 333-388.
- Kaplan, A.Ya., Fingelkurts, An.A., Fingelkurts, Al.A., Borisov, S.V., Darkhovsky, B.S., 2005. Nonstationary nature of the brain activity as revealed by EEG/MEG: Methodological, practical and conceptual challenges. *Signal Processing* 85, 2190–2212.
- Kelso, J.A.S., 1991. Behavioral and neural pattern generation: the concept of neurobehavioral dynamical system (NBDS). In: *Cardiorespiratory and Motor Coordination*. H.P. Koepchen, T. Huopaniemi, eds. Springer-Verlag, Berlin.
- Kelso, J.A.S., DelColle, J., Schöner, G., 1990. Action-perception as a pattern formation process. In: *Attention and Performance XIII*. M. Jeannerod, ed. Erlbaum, Hillsdale, pp. 139-169.
- Koch, C., 2001. Final Report of the Workshop "Can a Machine be Conscious". The Banbury Center, Cold Spring Harbor Laboratory, May 13-16. Available from: [http://www.theswartzfoundation.org/abstracts/2001\\_summary.asp](http://www.theswartzfoundation.org/abstracts/2001_summary.asp)
- Koch, C., Tononi, G., 2008. Can machines be conscious? *IEEE Spectr.* 6, 47–51.
- Köhler, W., Held, R., 1947. The cortical correlate of pattern vision. *Science* 110, 414-419.
- Kosslyn, S.M., 1980. *Image and Mind*. Harvard University Press, Harvard.
- Krippendorff's dictionary of cybernetics, 1989. In: Heylighen F, editor. *Web dictionary of cybernetics and systems* <http://pespmc1.vub.ac.be/ASC/OPERATION.html>

- Lee, M.H., 2007. Birkhoff's theorem, many-body response functions, and the ergodic condition. *Phys. Rev. Lett.* 98, 110403.
- 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.
- Lichtsteiner, P., Posch, C., Delbruck, T., 2008. An 128 x 128 120 dB 15 $\mu$ s-latency temporal contrast vision sensor. *IEEE J. Solid State Circuit.* 43, 566–576.
- Linåker, F., Niklasson, L., 2000. Time series segmentation using an adaptive resource allocating vector quantization network based on change detection. *Proceedings of the IEEE-INNS-ENNS International Joint Conference on Neural Networks*, pp. 323–328.
- Linkenkaer-Hansen, K., Nikouline, V.V., Palva, J.M., Ilmoniemi, R.J., 2001. Long-range temporal correlations and scaling behavior in human brain oscillations. *J. Neurosci.* 21, 1370–1377.
- Manzotti, R., 2006. A process oriented view of conscious perception. *J. Conscious Stud* 13, 7–41.
- Marchetti, G., 2006. A presentation of Attentional Semantics. *Cogn. Process.* 7, 163-194.
- Marchetti, G., 2009. Studies on time: a proposal on how to get out of circularity. *Cogn. Process.* 10, 7-40.
- Marchetti, G., 2010. *Consciousness, Attention and Meaning*. Nova Science Publisher, New York.
- Markram, H., 2006. The blue brain project. *Nat. Rev. Neurosci.* 7, 153–160.
- Mason, M.F., Norton, M.I., Van Horn, J.D., Wegner, D.M., Grafton, S.T., Macrae, C.N., 2007. Wandering minds: The default network and stimulus-independent thought. *Science* 315, 393-395.
- Maturana, H., Varela, F., 1980. *Autopoiesis and cognition: The realization of the living*. Boston Studies in the Philosophy of Science 42. R.S. Cohen, M.W. Wartofsky, eds. D Reidel Publishing Co, Dordrecht.
- McCarthy, J., 1995. Making robot conscious of their mental states. In: *Machine Intelligence*. Muggleton S (Ed.), Oxford University Press, Oxford.
- McFadden, J., 2002. Synchronous firing and its influence on the brain's electromagnetic field: Evidence for an electromagnetic field theory of consciousness. *J. Consc. Stud.* 9, 23–50.
- Mead, C., 1989. *Analog VLSI and neural systems*. Addison-Wesley, Reading, MA.
- Merolla, P.A., Arthur, J.V., Shi, B.E., Boahen, K.A., 2007. Expandable networks for neuromorphic chips. *IEEE Trans. Circuit. System I Fundam. Theory Appl.* 54, 301–311.
- Metzinger, T., 1995. *Conscious Experience*. Imprint Academic, Thorverton.
- Metzinger, T., 2003. *Being No One*. MIT Press, Cambridge.
- Metzinger, T., 2009. *The Ego Tunnel: The Science of the Mind and the Myth of the Self*. Basic Books, New York.
- Minsky, M., 1991. Conscious machines. In: *Machinery of Consciousness*. National Research Council of Canada.
- Minsky, M., 2006. *The emotion machine: Commonsense thinking, artificial intelligence, and the future of the human mind*, Simon and Schuster, New York.
- Nicolis, G., Prigogine, I., 1977. *Self-Organization in Non-Equilibrium Systems: From Dissipative Structures to Order through Fluctuations*. Wiley and Sons, New York.
- Novikov, E., Novikov, A., Shannahoff-Khalsa, D., Schwartz, B., Wright, J., 1997. Scale-similar activity in the brain. *Phys. Rev. E Stat. Phys. Plasmas Fluids Relat. Interdiscip. Topics* 56, R2387–R2389.
- Nunez, P. L., 2000. Toward a quantitative description of large-scale neocortical dynamic function and EEG. *Behav. Brain Sci.* 23, 371–398.
- Nunez, P.L., Srinivasan, R., 2006. A theoretical basis for standing and traveling brain waves measured with human EEG with implications for an integrated consciousness. *Clin. Neurophysiol.* 117, 2424-2435.
- Palm, G., 1990. Cell assemblies as a guideline for brain research. *Concepts Neurosci.* 1, 133-47.
- Perlovsky, L.I., 2006. *Modeling Field Theory for Higher Cognitive Functions*. Idea Group, Hershey.
- Plenz, D., Thiagarjan, T.C., 2007. The organizing principles of neuronal avalanches: cell assemblies in the cortex? *Trends Neurosci.* 30, 101–110.
- Pulvermueller, F., Preissl, H., Eulitz, C., Pantev, C., Lutzenberger, W., Elbert, T., Birbaumer, N., 1994. Brain rhythms, cell assemblies and cognition: Evidence from the processing of words and pseudowords. *Psychology* 5, brain-rhythms.1.pulvermueller
- Revonsuo, A., 2006. *Inner Presence. Consciousness as a Biological Phenomenon*. MIT Press, Cambridge.
- Rosenthal, D., 2005. *Consciousness and Mind*. Clarendon Press, Oxford.
- Rosenthal, D., Weisberg, J., 2008. Higher-order theories of consciousness. *Scholarpedia* 3, 4407.
- Sanz, R., Hernandez, C., Gomez, J., Bermejo-Alonso, J., Rodriguez, M., Hernando, A., Sanchez, G., 2009. Systems, models and self-awareness: Towards architectural models of consciousness. *Int. J. Mach. Consci.* 1, 255-279.
- Seth, A.K., 2009. The strength of weak artificial consciousness. *Int. J. Mach. Consci.* 1, 71–82.
- Shepard, R.N., Cooper, L.A., 1982. *Mental Images and their Transformations*. Cambridge University Press, Cambridge.
- Silvestri, L., Fronzoni, L., Grigolini, P., Allegrini, P., 2009. Event-driven power-law relaxation in weak turbulence. *Phys. Rev. Lett.* 102, 014502.
- Singer, J.L., 1966. *Daydreaming*. Plenum Press, New York.
- Singer, W., 2001. Consciousness and the binding problem. *Ann. N. Y. Acad. Sci.* 929, 123-146.

- Sloman, A., 2004. The architecture of brain and mind. The UK computing research committee Grand Challenges Conference at Newcastle, 29-31 March.
- Sloman, A., Chrisley, R., 2003. Virtual machines and consciousness. *J. Consci. Stud.* 10, 133–172.
- Stanley, H.E., 1987. Introduction to phase transitions and critical phenomena. Oxford University Press. Oxford, UK.
- Stening, J., Jacobsson, H., Ziemke, T., 2005. Imagination and abstraction of sensorimotor flow: Towards a robot model. Proceedings of the AISB05 Symposium on Next Generation Approaches to Machine Consciousness, Hatfield, UK.
- Tononi, G., 2004. An information integration theory of consciousness. *BMC Neurosci.* 5, 42.
- Treisman, A., Gelade, G., 1980. A feature-integration theory of attention. *Cognitive Psychology*, 12, 97–136.
- Trehub, A., 2007. Space, self, and the theater of consciousness. *Conscious. Cogn.* 16, 310–330.
- Turing, A.M., 1950. Computing machinery and intelligence. *Mind* 59, 433–460.
- van Dijk, J.B.J., 2006. Objects of thought, thoughts of objects: The creation of realistic and anti-realistic thought by object-oriented neurocognitive mechanisms. International Conference (Anti-) Realisms, Logic and Metaphysics, Nancy (France), June 28–July 1.
- van Leeuwen, C., 2007. What needs to emerge to make you conscious? *J. Conscious. Stud.* 14, 115-136.
- von der Malsburg, C., 1999. The what and why of binding: the modeler's perspective. *Neuron* 24, 95-104.
- von Müller, A.A.C., 2010. Thought and reality: A philosophical conjecture. About some fundamental features of human thinking. In: *Towards a Theory of Thinking: Building Blocks for a Conceptual Framework*. B. Glatzeder, V. Goel, A. von Müller, eds. Springer-Verlag, Berlin-Heidelberg, pp. 59-71.
- Werner, G., 2007. Metastability, criticality and phase transitions in brain and its models. *Biosystems* 90, 496–508.
- Werner, G., 2009. Viewing brain processes as critical state transitions across levels of organization: neural events in cognition and consciousness, and general principles. *Biosystems* 96, 114–119.
- West, B.J., Geneston, E.L., Grigolini, P., 2008. Maximizing information exchange between complex networks. *Phys. Rep.* 468, 1-99.
- Wijekoon, J., Dudek, P., 2008. Compact silicon neuron circuit with spiking and bursting behaviour. *Neural Netw.* 21, 524–534.
- Zapperi, S., Bakgaard, L.K., Stanley, H.E., 1995. Self-organized branching processes: mean-field theory for avalanches. *Phys. Rev. Lett.* 75, 4071–4074.