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Natural World Physical, Brain Operational, and Mind Phenomenal Space-Time

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Abstract

Concepts of space and time are widely developed in physics. However, there is a considerable lack of biologically plausible theoretical frameworks that can demonstrate how space and time dimensions are implemented in the activity of the most complex life-system – the brain with a mind. Brain activity is organized both temporally and spatially, thus representing space-time in the brain. Critical analysis of recent research on the space-time organization of the brain's activity pointed to the existence of so-called operational space-time in the brain. This space-time is limited to the execution of brain operations of differing complexity. During each such brain operation a particular short-term spatio-temporal pattern of integrated activity of different brain areas emerges within related operational space-time. At the same time, to have a fully functional human brain one needs to have a subjective mental experience. Current research on the subjective mental experience offers detailed analysis of space-time organization of the mind. According to this research, subjective mental experience (subjective virtual world) has definitive spatial and temporal properties similar to many physical phenomena. Based on systematic review of the propositions and tenets of brain and mind space-time descriptions, our aim in this review essay is to explore the relations between the two. To be precise, we would like to discuss the hypothesis that via the brain operational space-time the mind subjective space-time is connected to otherwise distant physical space-time reality.

Key words: spatial, temporal, consciousness, cognition, operation, architectonics, EEG, field, metastability, physics, coordinative dynamics, self-organization, cortex.

“The practice of giving preference to methodology over theory can retard progress in research since additional material and intellectual expenses are incurred as a result of overspecialization in research and the duplication of work on important basic problems. This, in turn, can cause a fragmented knowledge structure so that models and concepts have no validity beyond their own narrow research areas ... Only theoretical generalization can point to the optimal direction for research development”
(Lazarev [1]).

1. Introduction

This review starts with some general considerations for cognitive neuroscience and for brain and mind research. The history of brain-mind research over the last few decades clearly pointed to the fact that the physical (physiological) and mental (subjective) aspects of brain functioning should be considered as complimentary to each other rather than contradictory [2-4]. This idea was best expressed by one of the chief architects of quantum mechanics Pauli [5]: “To us the only acceptable point of view appears to be one that recognizes both sides of reality—the quantitative and the qualitative, the physical and the psychical—as compatible with each other. It would be most satisfactory of all if physics and psyche could be seen as complementary aspects of the same reality” (p. 260).

The complementarity of brain and mind is based on substantial empirical evidence about how brain and mind processes are coordinated in *space* and *time* [6,7]. Indeed, neurons in different brain parts oscillate at different frequencies [8-10] forming transient neuronal assemblies¹ [11- 15]. These neuronal assemblies are selectively coupled or “bound” together into a coherent network each time when a person attends, perceives, memorizes, imagines, thinks, plans, and acts [16-27]. During this dynamic self-assembling² process different neuronal assemblies *spatially* located in distant parts of the brain engage and disengage in *time*, much like different musical pieces in a symphony [30], paralleling the emergence and vanishing of different perceptual features, objects, full scenes, and even abstract ideas in a conscious mind [31].

Even though the notions of time and space have a long and somewhat confusing history, they are critical for understanding practically all observed phenomena. In physics they are used to formulate the fundamental laws. Physical ‘space’ and ‘time’ are crucial elements in theoretical

¹ 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 [10-13].

² Self-assembling or more accurately self-organization means that the resulting structures or functions are not imposed on the system from the outside but that the system finds them by itself [28,29].

physics; these concepts are widely developed and originated from our observations of the external material world. Indeed, as it is pointed by Primas [32], from our everyday experience we believe to know that certain aspects (patterns) of a holistic universe of discourse are quite independent of others, notably those distant in *time* or *space*. This observation has its best-known origin in the Aristotelian [33] and Kantian view [34], that the outer world is revealed to us both spatially and temporally. In physics, this observation has been embodied in the so-called *spatial-temporal separability principle*. According to Howard [35], this principle means that the contents of any two (and more) regions of space-time separated by a nonvanishing spatial-temporal interval constitute different physical systems³. In other words such systems possess their own distinct physical states and the joint state of such two systems is wholly determined by the individual separate states [32].

Since the notions of space and time are crucial for the understanding and analysis of a living brain and functioning mind, below we shall briefly review the notions of space and time as they are formulated in the most fundamental branch of science – theoretical physics. Here the main methodological approach is a detailed and systematical description of the phenomena in their own terms and at their own level of description.

1.1. Physical space

In an encyclopedia physical space is defined as a boundless, three-dimensional extent in which objects and events occur and have relative position and direction [37]. It is considered as one of the few fundamental quantities in physics, meaning that it cannot be defined via other quantities because nothing more fundamental is known at the present. However, it can be related to other fundamental quantities and can be explored via measurement and experiment.

Physical space typically deals with a large collection of ‘microscopic’ constituents which at a ‘macroscopic’ level display qualitatively novel features and properties [38]. Such macroscopic novel properties have no referent at the microscopic level; they create new physical states which call for new descriptions of physical reality [39]. The scale of space on each level emerges from the scale on the previous finer level by ignoring some of the lower-level details which are irrelevant for the higher level [40,41]. In the words of Werner [38], the macroscopic level can be viewed as an abstract rendition of the microscopic level.

³ It is also closely related to a principle formulated by Einstein [36]: “An essential aspect of [the] arrangement of things in physics is that they lay claim, at a certain time, to an existence independent of one another, provided these objects ‘are situated in different parts of space’.” This expression suggests that the “space” Einstein had in mind here was actually a space-time.

Such processes are the subject of Synergetics [28], which studies how the cooperation between the individual parts at the microscopic level produces structures or functions by means of self-organization at the macroscopic level [29]. Self-organization is the means by which a system shifts into a new configuration, allowing the system to offload the “unwanted” entropy⁴. At the same time, it is this same entropy that provokes self-organization in the first place [42,46]. Thus, changes in entropy provide an important window into self-organization: a sudden increase of entropy just before the emergence of a new structure, followed by brief period of negative entropy (or negentropy) [47,48].

At all scales, the constraints among micro-elements must break or loosen to some degree before the system as a macrostate can change [49]. The system of a particular level is governed by fixed parameters, the control parameters. When one or several control parameters approach a critical value the state of the system becomes unstable and is replaced abruptly by a new state⁵. At these critical points collective variables, the so-called order parameters, emerge at the macroscopic level. In general terms, order parameters determine the behavior of individual parts of a system at the microscopic level⁶, while at the same time being maintained in their actions by cooperation of the individual parts [28,29]. Thus, we are dealing with circular causality (Fig. 1).

1.2. Physical time

In an encyclopedia physical time is defined as the measured or measurable period during which an action, process, or condition exists or continues [51]. In physics time is considered to be one of the few fundamental quantities.

⁴ Entropy means that the amount of free energy in a system is always decreasing. This so-called second law of thermodynamics requires that all physical systems follow the same trajectory toward a final state, called equilibrium. Equilibrium is a thoroughly disordered regime, in which (a) there is no free energy and, therefore, no structure [42], (b) all distributions of matter and energy are homogeneous throughout, and (c) no portion of the system is distinguishable from another. The degree of disorder or lost energy is quantified as entropy [43]. All closed systems tend toward greater entropy over time [42,44]. Self-organization is a potential property of open systems. The distinction between open and closed systems is based on the interactions between a system and its environment. While closed systems do not exchange any energy with their surrounding environment, open systems do. In fact, many open systems “live” on a steady flow of energy. As energy enters into the system, some of it is consumed to do work for the system. The remaining energy produces fluctuations in the system, leading to a more disordered state at the microscopic scale. Thus, the influx of energy produces an increase in entropy [43]. In contrast to closed systems, however, open systems usually do not “bottle up” this entropy. Instead, open systems self-organize macroscopic structure for the purposes of offloading entropy into the environment. By doing so, they regulate energy flow and promote the emergence of macroscopic structure [44,45].

⁵ The word “state” is used here in a wide sense. It may refer to configurations, behavior, function, etc [50].

⁶ Since the number of order parameters is much smaller than that of the individual parts of the system, this allows for an enormous information compression [28,29].

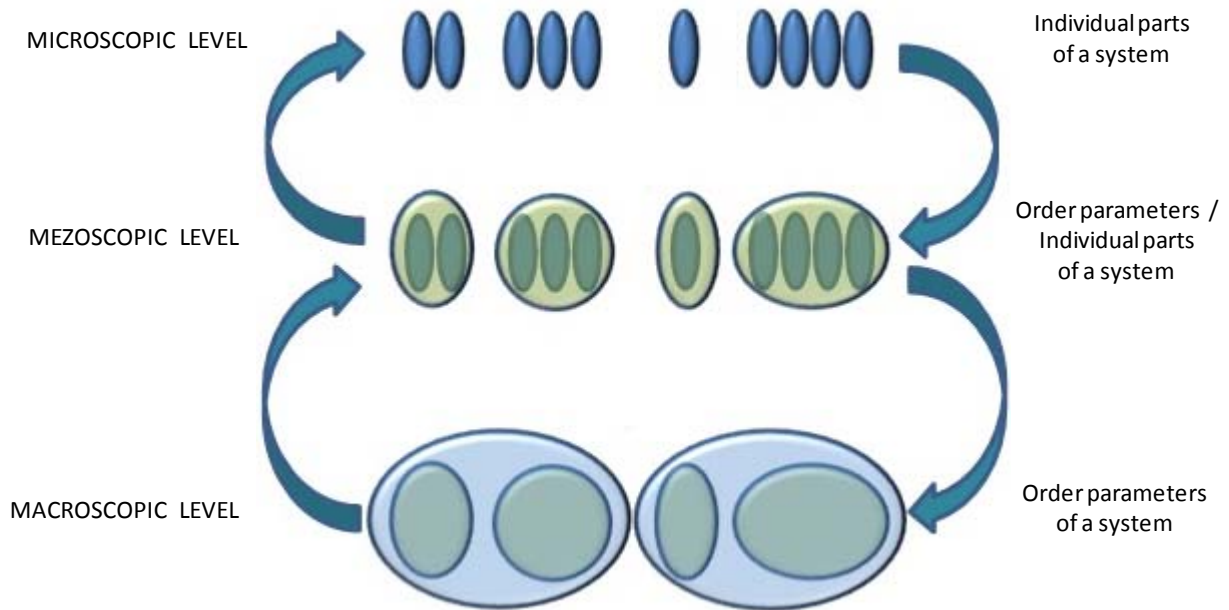


Figure 1. The hierarchy of levels with circular causality. Conceptually, the functional relations between and within levels of organization are often considered in terms of integration and differentiation where the larger scale is being ‘slaved’ to the smaller by some coupling function or circular causality.

Physical time is purely sequential, described by a tenseless relational parameter [52], and characterized by a number created by the processing of ‘energy of reconfiguration’ information carried by “signals”. The signal information represents the endpoint of a geometric and energy configuration change of the matter in a source system [53]. Indeed, as Marchetti pointed out, in fact, we usually think and talk about time not in time’s own terms, but rather in terms of motion through, and location in, three-dimensional space [54].

The standard theories of modern physics make no reference to an explicit “present” [55]. In the Newtonian view as well as according to the special and general relativity theories only a distinction between ‘causally related’ and ‘causally unrelated’ events is allowed⁷. Such temporal relations between events are causally directional. When one event precedes the other, the reverse cannot happen simultaneously [58]. The stream of material change has no duration on its own; one gives it

⁷ In agreement with the special and general relativity theories, for two causally unrelated events the attribute of simultaneity is not an objective statement but depends on the state of an observer [55]. Indeed, according to Einstein’s relativity theory [56], attributions of length or of temporal separation between events only make sense when they are understood as relative to a chosen frame of reference. Thus, observers moving relative to each other will disagree about the temporal and spatial separations between two events taken individually. However they will agree upon the spatial-temporal interval, which is the result of a measurement of spatial distances in three dimensions, with time as the fourth dimension. The result of the latter measurement, known as space-time distance, turns out to be the same for all observers, regardless of their state of motion [57]. To be more precise it is a matter of convention concerning the synchronization of clocks [55].

a sense of duration by measuring it with clocks and experiencing them into mind model of time. Thus, time exists only when we measure it.

This is the standard picture according to classical physics. On the other hand, when quantum systems⁸ have been considered by physicists, a “present” between the future and the past, which has the attribute of an extension⁹ (measured against a mathematical or hypothetical idealized “time”), was introduced (for a review see [60]). It has been suggested that the “width” of the time-space of the present depends on the specific event, which is taking place until the event becomes a fact¹⁰ in correlation with the extraction of information [55]. This view is compatible with human subjective experience.

Humans are able to subjectively experience only the “now,” or the “presence within time” [65-68]. According to Wackermann [69] beyond the phenomenal horizons of such “presence”, time is just cognitively (re)constructed, and not actually experienced or ‘perceived’ (we will continue this discussion in Section 3.2). The problem here is how to relate the “outer,” the so-called Aristotelian or “physical” time to the “conscious” time of experience, i.e. the time of Augustinus, and the Bergsonian time [70]. We will show in the Section 4 how this problem can be neurophysiologically overcome.

However, there is a considerable lack of biologically plausible theoretical frameworks which can demonstrate how space and time dimensions are implemented in the activity of the most complex life-system – the brain with a mind. Considering seriously the basic physical concepts of space and time in brain and mind functioning would place the entire Cognitive Neuroscience into a completely different framework of scientific reasoning [38], which would rest on the basic outlook in contemporary physics that observable properties in the physical world are represented as *spatial-temporal interactions* among the spatial-temporal patterns. Such patterns are defined as structures or dimensions in a state *space* with laws of *temporality* [71]. Accordingly, in the brain, a given level of a spatial-temporal organization can be viewed as coarse grained approximation of the previous level, each expressed on its own intrinsic spatial-temporal scale [38]. On the top of such spatial-

⁸ Quantum theory describes the behavior of the matter and energy which comprise the physical universe at a fundamental level. At the root of quantum theory is the wave/particle duality of atoms, molecules and their constituent particles. A quantum system such as an atom or sub-atomic particle which remains isolated from its environment behaves as a “wave of possibilities” and exists in a coherent complex-number valued “superposition” of many possible states [59].

⁹ The extended present is marked by a loss of sequentiality; meaning that it is impossible to attribute a sequential order to events which happen within this extended period [55].

¹⁰ Such a view can be traced back to Heraclitus, who focuses on change and processes of becoming. Up to the present days, probably the best known protagonist of such a “process-based” philosophy is Whitehead with his Process and Reality essay [61]. During recent decades, some physicists [62-64] try to relate Whitehead’s approach to modern concepts in quantum theory.

temporal hierarchy one can observe the phenomenal level of brain organization – conscious awareness [72].

1.3. Summary of this review essay

This review is organized as follows. After formulating a contemporary problem in brain and mind research and a brief reminder of basic physical concepts such as space and time, which are crucially important to understand brain and mind as a unified continuum (Section 1), we present a literature analysis on how space and time are implemented in the brain (Section 2). Then we move to the phenomenological (subjective) domain, and analyze the space-time organization of a mind (Section 3). Subsequently, in Section 4, we will present the integration of space-time organizations of brain and mind within the unified Operational Architectonics framework [25,30] after a brief reminder of the main tenets of this framework to the reader. The concluding Section 5 contains a summary of the integration provided in the previous section and some comments on implications and predictions of space-time dynamics for further research of brain and mind.

Our aim in this essay review is multifold: (a) to review the physical concepts of space and time, (b) to discuss the spatial-temporal activity of the brain and spatial-temporal organization of the mind in the context of contemporary neuroscience and phenomenological studies correspondingly, (c) to explore the relations between the two within an integrated framework, and (d) to comment on how the mind subjective space-time through brain operational space-time is connected to the otherwise distant physical space-time reality.

This requires us to engage in an uneasy balancing act of description. The set aims of this review require a multi- (or cross-) disciplinary effort. Given the known relativity of boundaries between scientific branches we cannot rely completely on any one scientific perspective. As history of science shows, the mono-paradigmatic approaches are risky as they only tell part of the story.

Although this review article is presented as a synthesis, we have chosen to include a large corpus of quotes and references in order to provide the reader with concrete points of access to the broad spectrum of complex ideas, concepts, and terminology¹¹. We have also used a system of notes so as not to interrupt the flow of the text.

One more note: In this review we will use an informal way of description (modeling and mathematical aspects will not be elaborated here), hoping that the lack of technical detail will be

¹¹ Many of these terms and concepts present a challenge since they either have not been uniquely defined and their meaning is a subject of active research and ongoing debates, or they are based on sophisticated theoretical analysis or philosophy. As a result, different scientists use them in many ways colloquially.

seen as a welcome attempt at maintaining intelligibility for a broader audience. Even though the full mathematical and modeling descriptions related to mind (or mind-brain system) are largely still to be devised, several interesting formulations have already emerged: The Perlovsky's Modeling Field Theory¹² (MFT) of mind [73], the Lehar's Gestalt Bubble Model¹³ (GBM) of subjective experience [74], and the Khrennikov's Cognitive Quantum-like Model¹⁴ (CQM) of brain functioning [75].

2. Space and time in the brain

In this Section, we will look at how the rather abstract principles of space and time described in the previous Section might be applied to the brain. A brain, like any physical system¹⁵, is also organized around principles of space-time dynamics. However, the spatio-temporal ordering observed in all levels of the operating brain is functional and task-specific [3].

Despite the enormous number of neurons and their interconnections in the human brain cortex ($\sim 10^{11}$ neurons and $\sim 10^{14}$ synapses¹⁶), the brain organization is ruled by optimizing principles of resource allocation and constraint minimization [76,77]. From a functional perspective, the spatio-temporal brain organization is necessitated by evolutionary pressure [78]: In the space-constrained skull, more computational efficiency is obtained by grouping together (*space aspect*) neurons with similar function and denser interactions on a particular time scale (*temporal aspect*), so that the overall number of interconnections is minimized [79-81]. Indeed in the course of the evolution of the brain, the number of neurons has considerably increased, whereas their connections have become less direct [79,82,83], thus minimizing costs of interconnection between neural sites, and yielding efficient communication between them [84-87].

For the purpose of this review we will focus mostly on the cerebral cortex¹⁷ as an essential component of brain-mind interaction [78]. The cerebral cortex (as well as the whole brain) operates

¹² The MFT mathematically implements the main organizational features of a mind. Its main premise is that the same laws describe the basic interaction dynamics at each level of mind hierarchy.

¹³ The GBM theory introduces a computational approach to holistic aspects of three-dimensional scene perception. The model has merit because it manages to translate certain Gestalt principles of perceptual organization into formal codes or algorithms and show how they can be encoded neurophysiologically.

¹⁴ The CQM introduces the quantitative measure of mentality and mathematically defined consciousness in nervous system or any other complex cognitive system.

¹⁵ The brain is also a synergetic system, which implies that it operates close to instabilities and achieves its activity by self-organization which leads to the emergence of new qualities [50].

¹⁶ A synapse is a specialized junction between two neurons or other cells through which neurons signal/communicate with one another and to non-neuronal cells (such as those in muscles or glands). Synapses allow neurons to form circuits within the central nervous system.

¹⁷ The importance of the cortex for conscious awareness has been clearly demonstrated in an experimental study by Sahraie et al. [88]. Researchers compared two brain activities in a single blindsight subject (G.Y.); one was generated by stimuli which give rise to awareness, the other was 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

on a range of multiple spatial-temporal scales [91], which are ordered in an unified hierarchical organization¹⁸ [92,94-96]. Each level is macroscopic to that below it and microscopic to that above it. As pointed by Freeman [97]: “Among the most difficult tasks scientists face are those of conceiving and describing the exchanges between levels, seeing that the measures of time and distance are incommensurate, and that causal inference is more ambiguous between levels than it is within levels, especially when the distance between levels is wide” (p. 3-4).

Below we shall briefly review the three main spatial-temporal scales of the cortex organization: micro-, meso-, and macroscopic levels.

2.1. Microscopic level of brain organization

Microscopic scale refers to the activity of single-neurons with their sparse networks of dendritic bundles (Fig. 2 A) [98]. Individual neurons are considered as the basic signaling elements of the brain [8]. On average, each square millimeter of the human neocortex contains ~50 000 neurons, while each cubic millimeter contains ~ 10^9 synapses [99]. Each neuron has ~5 000–10 000 direct connections with other neurons [100]. It was calculated that an individual neuron performs ~200 computations/operations per second [101]. Neurons can be excitatory and inhibitory¹⁹. Excitatory neurons are generally pyramidal (triangular shaped) and have their dendrites aligned approximately perpendicular to the surface of the cortex (axial to the macrocolumn – to be defined in the next section). The field at the surface of the cortex, due to currents following along the dendrites of these neurons, can be approximated by a dipole term [102]. In contrast, inhibitory neurons generally have their dendrites randomly dispersed, with approximately spherical symmetry. This spherical symmetry leads to a much smaller field at the surface of the cortex [103].

Anatomical data directly suggests that the dendritic fields of individual cortical neurons would result from the appropriate environmental stimuli, to which the neurons are exposed, thus relating structural brain organization and function in a causal manner [104]. For example, in stripe-reared kittens cortical neurons in the visual cortex become elongated and narrowed in sections tangential to

pattern of activity from cortical to subcortical levels. Nunez [89] also has shown that subcortical activity is only weakly correlated with conscious cognition and behavior. Furthermore, it has been demonstrated that dreams (which is the subjective experience in a pure form; see Section 3) are almost entirely dependent on the cortex [90].

¹⁸ It has been suggested [92] that architecture of the cortex (brain) is characterized by “a modular organization repeated across a hierarchy of *spatial* scales—neurons, minicolumns, cortical columns, functional brain regions, and so on. It is important to consider that the processes governing neural dynamics at any given scale are not only determined by the behavior of other neural structures at that scale, but also by the emergent behavior of smaller scales, and the constraining influence of activity at larger scales”. For similar conceptualizations see also [3,6,25,30,78,93].

¹⁹ A voltage impulse arriving at the neuron is classified as inhibitory if it tends to make the soma voltage more negative and therefore less likely to reach threshold, and excitatory if it raises the soma voltage towards (or above) threshold.

the pial surface, when compared with those measured in normally reared kittens [105]. In such stripe-reared kittens, the anatomical orientation axis of the dendritic arborization in the horizontal cortical layer plane would thus reflect the topological projections of the experienced stripes, through the interplay of activity-dependent processes [104].

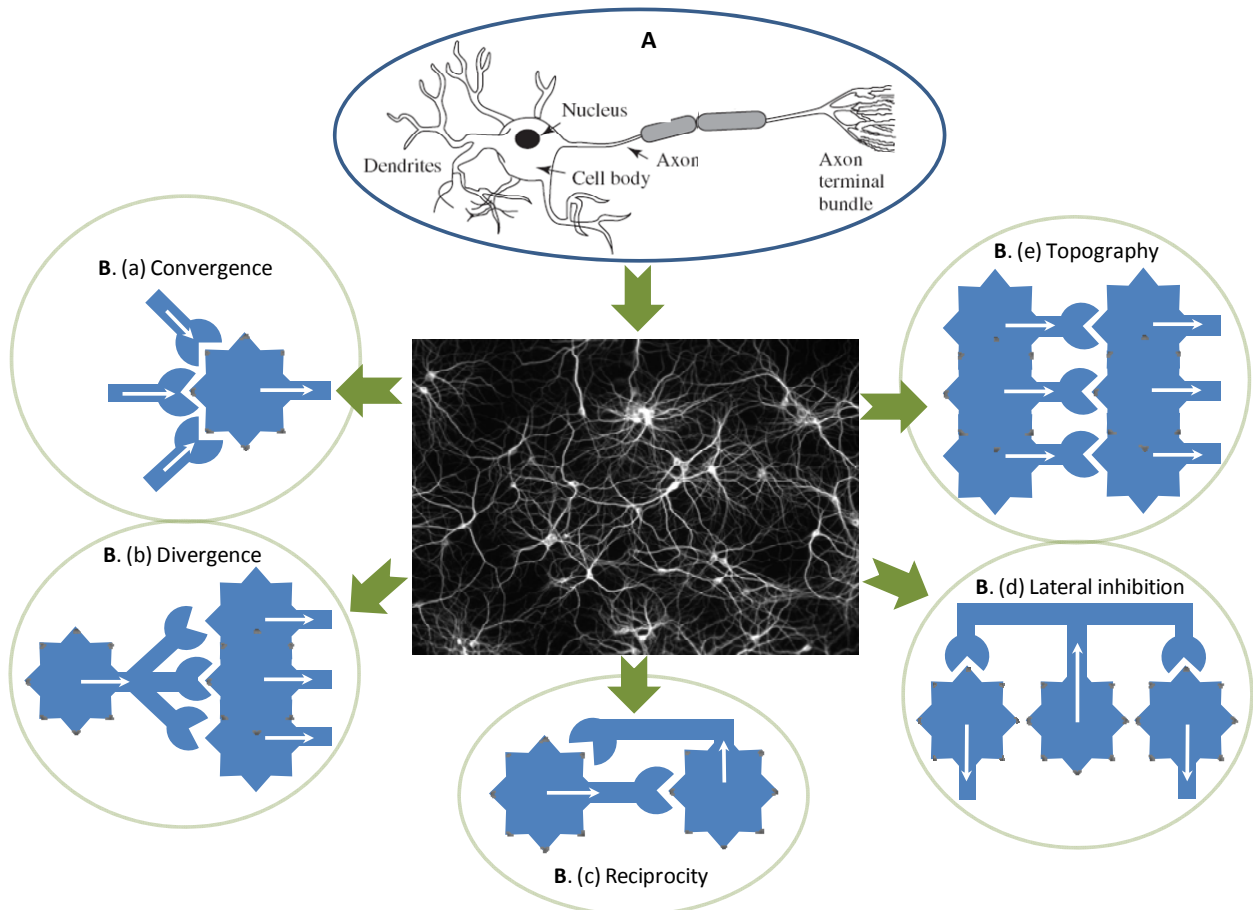


Figure 2. Neuron organization (A) and typical patterns of neural (anatomical) connectivity (B). (a) Convergence connectivity – supposed to have a role in the merging of information; (b) Divergence – supposed to enable a wide “broadcast” of information; (c) Reciprocity – supposed to have an important role in the maintenance of information over time; (d) Lateral inhibition – is involved in suppression of competing neural responses; (e) Topographic projections – supposed to enable the rapid and faithful relay of information. Arrows represent the flow of activation passing through cells (blue figures). Insertion in the middle of the figure is an example of the connected neuronal net.

The activity of neurons (which are located in different *spatial* locations) evolves in *time*, because the activity of each neuron is determined by the activity of neurons at an earlier temporal interval and the activity of the excitatory or inhibitory synapses located between them [106]. In the early years of research, it was thought that the firing rate of individual neurons could carry all the

necessary processing information [107-109]. However, latter it was found that firing rate of individual neurons cannot represent images of objects or processes extending in *time* and *space* [6], therefore, it was concluded, that firing rate faces several problems [110]. First, the inherent activities of isolated neurons can fluctuate within only a narrow dynamic range, whereas the input signal amplitudes can often vary over a much wider dynamic range [111]. The neurons' small dynamic range could hereby make them insensitive to both small and large inputs as a result of noise and saturation, respectively, at the lower and upper extremes of the neurons' dynamic range. Therefore, interactions across many neurons within a neuronal assembly are needed to preserve information about the relative sizes of inputs to the neurons in the assembly²⁰, and thereby overcome noise and saturation [111]. Second, it is generally accepted that the firing rate of an individual neuron contains information about the properties of the activating stimulus. This information would be lost if the neurons of the same assembly would all fire with the same rate. Third, the firing rate 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 [112]. Fourth, experimental findings do not support the assumption that neurons respond only in discrete frequency steps but show that they are continuously dependent on various stimulus properties like orientation, direction or spectral composition [113].

In most situations, isolated individual neurons are ineffective in triggering responses in target areas to which they project [114,115]. Another limitation of single neurons is the fact that separate neurons could not fire faster than a few milliseconds [116]. However it is known that brain as a whole can discriminate times that are much briefer (as small as only a few μsec) [117,118]. Moreover, the intrinsic properties of each neuron vary over time (neuron dynamics changes continuously). Most single neuron activity is expected to be determined by the activity of its peers and only a small fraction of this activity is determined by the features of the environment [15]. This renders the neurons able to continuously change or establish new connections according to computational and communication needs. Interactions between neural elements, being highly dynamic [119], are therefore more important than individual neurons per se.

When we record activity from the single cells, we observe brain activity at a very low level of organization – we trace the elemental brain physical operations. Such observations never allow the visualization of the phenomenon (cognition or mind) we are interested in (for a detailed discussion, see [31]). For these reasons it has been suggested that the activity of any individual neuron is

²⁰ The cooperative-competitive interactions that preserve neuron's sensitivity to relative input size also bind these cell activities into functional units, since relative activities can be computed only synchronously.

informative only insofar as it contributes to the overall statistics of the population of which it is a member.

It is likely, then, that the *temporally* joint action of several tens to hundreds of neurons (organized *spatially* in a local assembly) is minimally necessary to understand and explain the emergent cognitive and conscious phenomena [14,25,30,71,120]. Furthermore, several such assemblies in one cortical area are synchronized with a set of local assemblies in distant brain areas [67,121,122]. Stam [123] expresses it in the most explicit way: “Neurophysiology has become neuron-physiology, and later molecular biology of the neuron. However, ironically, the answers to some of the key questions cannot be found at the most fundamental level. There is no ‘molecule’ of memory, or consciousness, although, no doubt, many molecules are involved in both memory and consciousness. Nor is the current hype of ‘genomics’ and ‘proteomics’ likely to be of much help either. The problem here is that a purely reductionistic approach, while successful in other branches of science, does not suffice to explain how higher brain functions are organized. Higher brain processes depend upon interactions of multiple brain regions, and these interactions are complex, and, most likely, nonlinear”.

In our opinion the understanding of mentioned cognitive and conscious phenomena in relation to a brain requires assessment of meso- and macroscopic levels of brain organization, as well as an adequate conceptual framework [4].

2.2. Mesoscopic level of brain organization

Mesoscopic scale refers to the coordinate behavior of local neuronal assemblies as measured by local field potentials and electroencephalography²¹ (EEG) [132]. According to Freeman [98, 132], mesoscopic effects operate at spatial scale of ~1 cm and temporal scale of ~100 ms and, thus, mediate between the two extremes of cortex organization: single neurons and the major lobes of the forebrain²². It is supposed, that these mesoscopic effects correspond in size to Brodmann's areas and in duration to mental (phenomenal) events that compose percepts. Mesoscopic effects provide a link between extreme local fragmentation and global unity in the cortex. They change continually in

²¹ Electroencephalogram (EEG) – The continuously changing electrical signal recorded from the scalp of the head that reflects the summated postsynaptic potentials of cortical neurons in response to changing physiological, cognitive, perceptual or mental states. The EEG can be measured with extremely high temporal resolution (~few milliseconds). Traditionally it has been considered that the discovery of EEG has been done by Berger in 1929 when he observed a nearly sinusoidal 10 Hz “brain waves” [124]. However, macroscopic brain potentials (EEG) were systematically registered much earlier: In 1875 by Caton [125], in 1877 by Danilevsky [126], in 1890 by Beck [127], in 1899 by Larionov [128], in 1899 by Trivus [129], in 1912 by Pravdich-Neminsky [130], and by Kaufman [131].

²² In physics, as opposed to neuroscience, the importance of intermediate-range effects is well recognized [133].

space and *time*, requiring a very close relationship between dynamic events, e.g., EEG bursts, and the media through which the propagation occurs [132,134].

Katchalsky was a pioneer in studying the collective behavior of neurons [135]. He stressed that computations and information transfer in the cortex are accomplished via spatial-temporal patterns of functionally related neurons: "...waves, oscillations, macrostates emerging out of cooperative processes, sudden transitions, patterning, etc. seem made to order to assist in the understanding of integrative processes of the nervous system ..." [136].

One way for neurons to communicate with one another within the neuronal assembly is through axons and dendrites [137-139]. There are several typical pattern types of connectivity among neurons²³ found throughout the brain: (a) convergent connections (many-to-one [141]) (Fig. 2 Ba), (b) divergent connections (one-to-many [142]) (Fig. 2 Bb), (c) reciprocal connections (corticothalamic projections [143]) (Fig. 2 Bc), (d) local inhibitory connections (among pyramidal cells of cortex [144]) (Fig. 2 Bd), and (e) topographic connections (one-to-one [145]) (Fig. 2 Be).

It is supposed that each type of connections exists to support a distinct sort of computation [139]. Topographic-type of connections among neurons is extremely widespread in the cortex. They contribute to transmitting spatially ordered information and also to several types of complex mental operations²⁴, including reasoning and analogy making [148].

Another way for the neurons to communicate within neuronal assemblies is by means of oscillations. Intrinsic oscillatory activity of single neurons forms the basis of the natural frequencies of neural assemblies [9]. Research has shown that neural assemblies in the cerebral cortex, hippocampus or cerebellar cortex are all tuned to the same frequency ranges²⁵ [150-154]. Different frequencies appear to be related to the *timing* of different neuronal assemblies (activated parts of network), which are associated with different types of sensory and cognitive processes [10,13-15,27,155,156]. The general assumption is that the functional interplay between units of the same

²³ Recent evidence indicates that the excitation wave of a given neuron needs to arrive within a fixed time window at target neurons located at multiple spatially remote sites at variable distances, – almost simultaneously at each target cortical cell [140]. It has been supposed that it is the difference of myelination that plays a major role in creating isochronicity: Myelination is not just insulation of the neuron's axons as previously thought, but is a natural mechanism for regulating the timing of communication between neurons [140].

²⁴ For example, Pulvermuller [146] observed the possibility that regions of the cortex organized by such connections among neurons might directly connect different features of words. Indeed, a representation of the word "rose" requires a combination of visual image (most likely represented in the visual cortex), smell (olfactory cortex), soft texture (somatosensory cortex), etc. Another function of such neuronal assemblies can be related to the organization of similar mentally represented concepts, according to Simmons and Barsalou [147].

²⁵ These findings support the suggestion that all brain networks communicate by means of the same set of frequency codes expressed through EEG-oscillations [149].

assembly or between different assemblies is based on a coordinated timing that is enabled by oscillations²⁶.

In congruence with this view, the traditional functional “maps” of the cortex should then be seen not as the static units suggested by Hubel and Wiesel [159,160], but rather as dynamic and transient ensembles (for the review see [25]), the state of which reflects not just the spatial interaction of local and long-distance networks, but most importantly their *spatio-temporal* interactions.

Recent studies based on the comparison of diffusion imaging and resting state functional magnetic resonance imaging (fMRI) data reveals a close relationship between structural and functional²⁷ connections [162], stressing that neuronal assembly is a set of neurons with both strong structural and synchronized functional connections.

2.2.1. Spatial structure of neuronal assemblies

The cortical minicolumn is a likely candidate for the structural component of the single neuronal assembly [78]. It is an anatomically (spatially) distinct circuit of about one or two hundred neurons, oriented perpendicularly to the surface of the cortex (Fig. 3), within which the autonomy of individual neurons is reduced [163] due to dense intrinsic connectivity [164-166]. It is supposed that minicolumns possess relatively stereotypic internal processing, and maintain generic patterns of inputs and outputs with minicolumns in other regions [167,168].

At the same time, about 1000 minicolumns are aggregated into a macrocolumn (Fig. 3), forming a much coarser structure of neuronal assembly [169,170]. A macrocolumn has a spatial extent of about a few millimeters [98,171,172]. It is argued that typically only several macrocolumns, that fire coherently, produce neuronal assembly’s electric potentials (Fig. 3) measured by one scalp EEG²⁸ electrode (Fig. 4) [173]. In sensory areas, such neuronal assemblies have been identified as functional units, because their tuning properties are quite homogenous within a neuronal assembly, but manifest sharp transition between neighbors.

²⁶ Izhikevich [157] proposed that by changing the frequency content of bursts and subthreshold oscillations, the brain determines which neuronal assembly talks to which at any particular moment. In this sense, the brain can rewire itself dynamically on a time scale of milliseconds without changing the synaptic hardware [157]. Thus, various neuronal assemblies can process information without any cross interference. Cortical neurons may participate in different assemblies simply by changing its frequency [158].

²⁷ However, one needs to keep in mind that functional connectivity is not necessarily due to structural/effective connectivity and, where it is, the structural/effective influences may be indirect [161].

²⁸ It has been suggested that EEG provides the best available assay of the local mean field intensities of cortical neuronal assemblies [97].

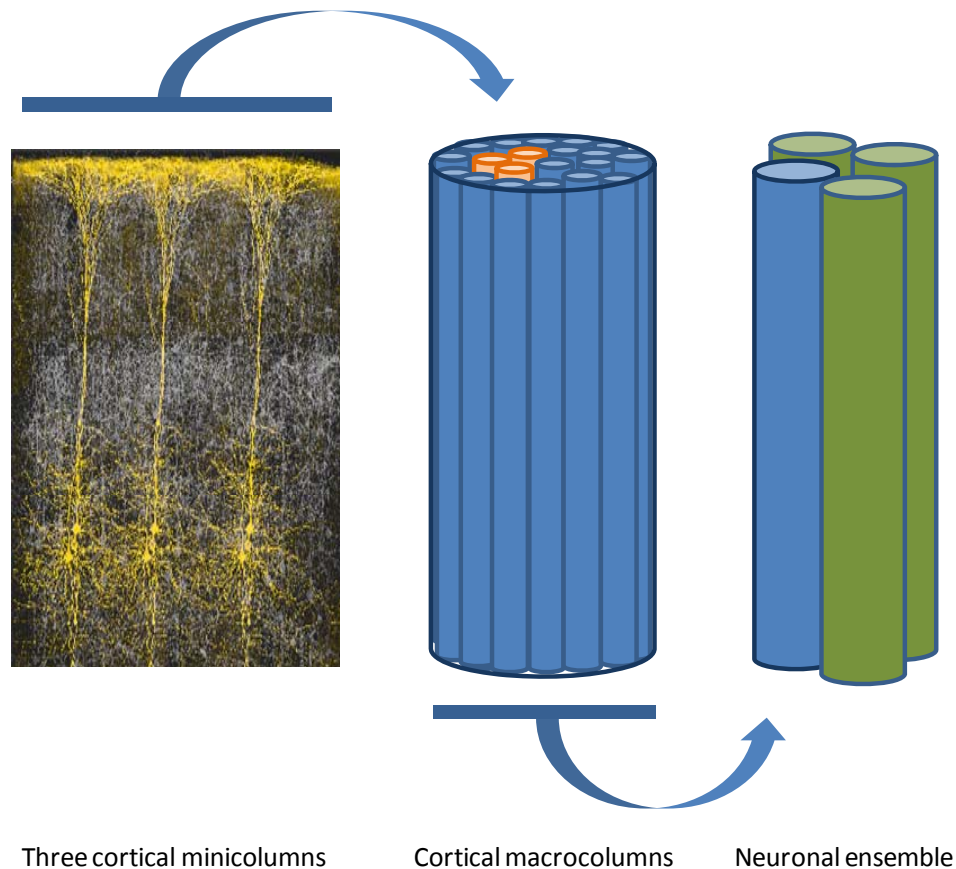


Figure 3. Columnar organization of the neocortex. The neocortex is organized into thousands of columns of neurons each of which is characterized by a particular structure: several minicolumns (shown as yellow neuronal conglomerates) organize a macrocolumn (shown as blue cylinder which consists from many minicolumns). In their turn, several macrocolumns organize the neuronal assembly.

One important spatial feature of neuronal assemblies is the finding that neuronal assemblies could overlap so that, for example, one column could simultaneously be part of several neuronal assemblies [172,173]. In this view, neuronal assemblies have substantial hierarchical structures at different spatial scales.

It implies that so-called “neurogeometry” [104] would constrain the physical substrate of the binding architecture of the cortex, and thus corresponds to the morphological embodiment of cognitive percepts. For example, it has been shown experimentally that global capacity for forming associations, specific to the visual system of humans and higher mammals, stems from implementation at the biological hardware level (cortical visual areas) of predefined constraints between the coding of the position in space and orientation [174,175].

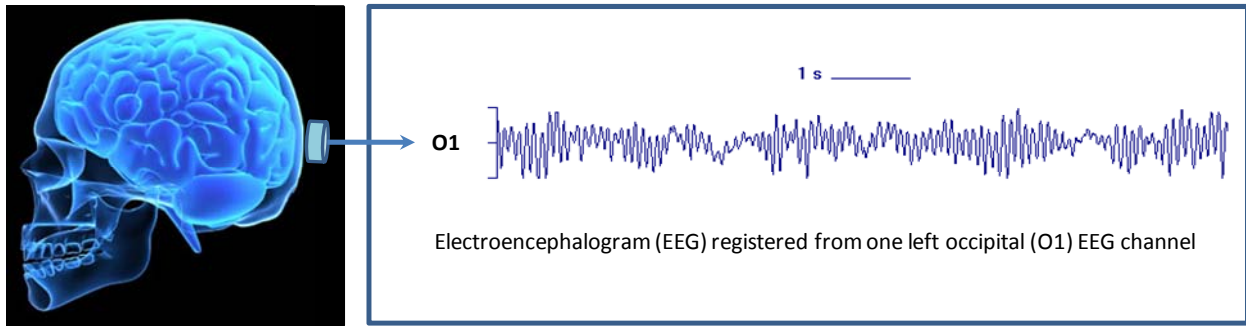


Figure 4. An example of an electroencephalogram (EEG) signal. The wave-like structure of EEG signal is self-evident.

2.2.2. Temporal structure of neuronal assembly

It has been shown that neuronal assembly occurs (or re-occurs) within 10-30 milliseconds [176]. This time-scale is of particular physiological significance, because it closely matches the membrane time constant – excitatory post-synaptic potential (EPSP) width of pyramidal neurons [177]. Recently Segev et al. [178] performed long-term measurements of spontaneous activity of in vitro neuronal networks laced on multi-electrode arrays. These developing networks show interesting temporal and spatio-temporal properties on many time scales including the formation of neuronal assemblies through the emergence of synchronized bursting events [179].

Experimental research has shown that each active neuronal assembly has its own fine temporal structure [110,113,180-184]. Neurons which are tuned to respond to the same feature of a complex stimulus are engaged in an episode of synchronous activity and thereby identify their activity as part of a population-coded signal produced by the distributed processing of a unified assembly [182]. Neurons of a second assembly would also synchronize the temporal structure of their activity within the range of different time-scale, but would avoid synchronization with the first and any other assembly. Precise synchronization therefore is a label²⁹ for signals evoked in the same neuronal assembly [110,113].

²⁹ Such a mechanism does not require compromising the rate-code containing stimulus specific information. Synchronization or desynchronization only require to shift individual spikes by a few milliseconds backward or forward in time but do not need a change of their average probability of occurrence which determines the rate [113]. The results of animal experiments indeed demonstrate that even well-isolated individual neurons can change dynamically their synchronization independent of rate changes [185].

It is important to stress, that the same neurons can participate in a large number of different assemblies, however at different time-scales [25]. For example, two neurons which are activated by the same stimulus and therefore belong to the same assembly in the next moment may be activated by two different stimuli. They will then belong to two different assemblies which process different stimuli in a different manner. The general rule³⁰ is that neurons which are activated by the same stimulus are synchronized, while if they are activated by different stimuli, should not synchronize [113].

However, such conceptualization has a limitation: The described neuronal assemblies have no flexible means of constructing higher-level operations by combining more elementary operations [186]. This problem is known as “the binding problem” [187]. To illustrate this, let us consider the following classical example: Imagine that *two features* of the same object need to be activated/represented in the *same* mental state in order to be integrated within the *unified mental image* of this object. Such co-activation would inevitably lead to what has been named a “superposition catastrophe”, whereby two neuronal assemblies responsible for two features of the same object will merge into one single assembly, and there will be no possibility for the brain (according to a classical neuronal assemblies concept) to express the information needed to subdivide the composite mental image of the object into its components [13]. One of the possible solutions for this problem will be offered in the Section 4.

The cortical neuropil composed of neural assemblies provides a medium for *spatio-temporal pattern(s)* formation of neural activity [188]. However, in contrast to a typical pattern formation in physical or chemical systems [28,29], a neural system has a spatially variant connection topology in which a cortical area consisting of several neuronal assemblies is not only connected to its nearest neighbors, but also has projections to distant neuronal assemblies located in remote cortical areas. By these means the nervous system accomplishes a directed transfer of activity within a continuous sheet in which it would spread out uniformly otherwise [188]. Such projections may not only serve to organize local dynamics within cortical areas such as synchronization of local rhythms, but also contribute to the macroscopic organization of neural activity or global EEG dynamics [3,78,89,189-193].

³⁰ This rule contrasts with the earlier assumption that correlated discharges reflect the anatomical properties of a network of neurons and are therefore largely independent on stimulus properties and of no particular functional relevance.

2.3. Macroscopic level of brain organization

Macroscopic scale refers to relations between many local neuronal assemblies located in close and distant cortical areas. The local field potentials (or the “wave packets” as Freeman [97] names them), which are the unified mean-field potentials of neuronal assemblies generated by the synchronized activity of thousands of neurons in the extracellular space of the cortical sheet, are understood to generate the EEG [97,132]. The neuronal cell membranes, being good electrical insulators, guide the flow of both intracellular and extracellular currents and, thus, result in a current flow perpendicular to the cortical surface due to the perpendicular alignment and elongated shape of pyramidal neurons [194]. The neuronal assemble average of these currents results in the primary current density with the same waveform and mean frequency over the entire neuronal assembly [195]. Such unified mean-field potentials are the site of the sources of brain activity and in sum denoted by the so-called neural field (EEG) (Fig. 5) which is characterized by the location on the two-dimension folded cortical surface (*space*) and the dynamics (*time*) [188,196, 197].

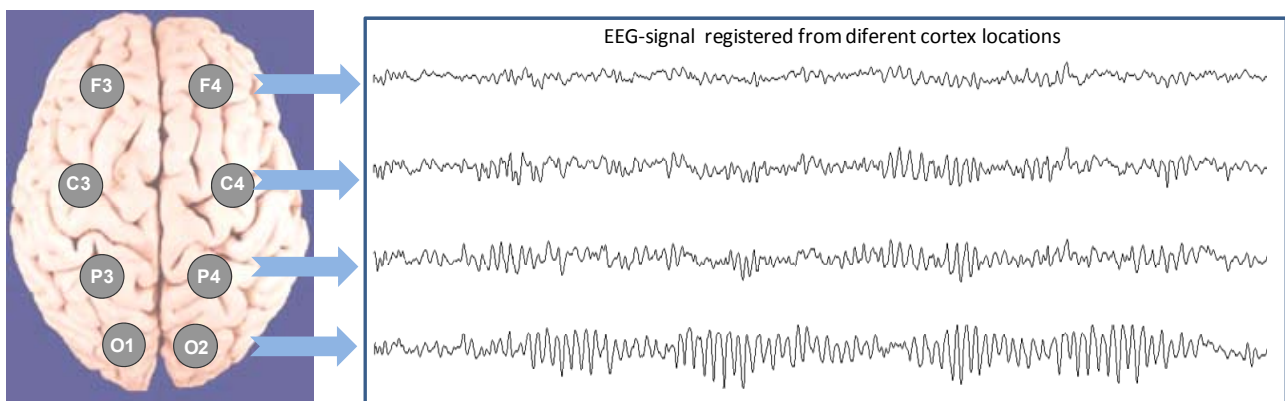


Figure 5. An example of multichannel EEG. The structure of EEG signal changes over time (see each local EEG signal) – temporal aspect; and this dynamics is different in each location of the cortex – spatial aspect. Labels of the cortical locations correspond to the International Standard for the EEG electrodes placement: F – frontal; C – central; P – parietal; O – occipital.

Because the unified mean-field potentials of neuronal assemblies are wave-mechanical phenomena, the magnitude of their modulations will be proportional only to the number of those neurons that synchronize their operations (postsynaptic potentials) [23]. Indeed, for neurons that are arranged randomly, their induced unified fields will tend to sum to zero; but the assembled organization of neocortex, with the hierarchy of spatial-temporal mosaics of neuronal assemblies,

will tend to amplify unified mean-field potentials of local neuronal assemblies (see the important studies of Bullock and coworkers [198,199]).

However, as it was reasonably pointed out by McFadden [23], for any induced unified mean-field to have a significant effect, its strength would be expected to be greater than the spontaneous random fields generated by thermal noise in the neuronal membranes. The neuronal voltage fluctuations due to thermal noise has been estimated to be 2 600 V/m for the frequency range 1–100 Hz (which is a typical for the mammalian brain waves frequency range) [200]. According to McFadden calculations [23], these values would mean 13 μ V across a 5 nm cell membrane, – the value which is well below the several millivolt transmembrane signal that is expected to be generated by the brain’s endogenous extracellular electromagnetic fields. Therefore, one may conclude that unified mean-field potentials of local neuronal assemblies must influence neuronal computations and serve as Haken’s order parameters [28,29].

2.3.1. Global versus local cortical processing

Bartels and Zeki [201] propose the notion of “temporal fingerprints” of different cortical areas, thus stressing the fact that distinct regions have a preference to process distinct features (such as a preference for color, smell, motion, actions, emotions or reward) [202]. Indeed, it has been shown experimentally that the intensity with which each of these features is perceived correlates linearly with the intensity of activity in the regions specialized for each feature [203]. Moreover, it was shown consistently across subjects that the maximum activity of areas with known specialization correlated with the presence of the corresponding feature [204].

Even though, evidence that the cortex operates through specialized processing streams [205] supports the idea that cortex processing is specialized and localized it does not, in itself, imply that these streams are completely independent from each other [111]. According to Grossberg [111], independent cortical areas should be able to fully compute their particular processes on their own. However, much of perceptual data argue against the existence of fully independent cortical centers, because strong interactions are known to occur between perceptual qualities [206-210]. For example, changes in perceived form or color can cause changes in perceived motion, the reverse is also true. Another example: Changes in perceived brightness can cause changes in perceived depth, and conversely [111]. Indeed, signals belonging to different sensory modalities are processed at

different speeds in distant neural regions, but to be useful to the organism as a whole, these signals must become *aligned in time*³¹ and also correctly tagged to outside events [213,215].

These considerations suggest that brain integrative functions are the result of competition of complementary tendencies of cooperative integration and autonomous fragmentation among many distributed areas³² [3,25,30,218]. The interplay of these two tendencies (autonomy and integration) constitutes the metastable³³ regime of brain functioning [223], where local (autonomous) and global (integrated) processes coexist as a complementary pair, not as conflicting principles [2,222].

This emergent metastable dynamics directly constitute the complex dynamics of the EEG field [25,30,97,132,189,190,222].

2.3.2. Electroencephalogram

An EEG (or more generally electro-magnetic) field³⁴ has structural and dynamic properties enabling the brain, which produces it, to register and appropriately integrate disparate stimuli (or internal mental images) into a unified and coherent spatial-temporal pattern(s) [23,97,132,225,226].

A striking feature of EEG, noticed since its first observation [124-131], is the differences in electrical activity (*temporal aspect*) from electrode to electrode location (*spatial aspect*) (see Fig. 5), even when electrodes are located less than 1 mm apart [198,199,227,228], indicating that the brain generates a highly structured and dynamic extracellular electric field [23]. For example, in classic experiments of Freeman [229-231] EEG activity was measured within the olfactory bulb of rabbits and cats; and the existence of spatially structured bursts of EEG activity was demonstrated in response to sensory stimuli with average amplitude of about 100 microvolts across recording

³¹ The “state-dependent networks” model proposed by Buonomano and Merzenich [211] suggests that the ubiquity of time-varying neuronal properties allows spatially remote neuronal assemblies to inherently encode temporal information. In other words, the way the network of neuronal assemblies evolves through time can code for the time itself. Therefore time is not encoded explicitly, rather, time is encoded in a space-time pattern [212]. Results of computer simulations [213,214] also indicated that temporal information is encoded in the context of the entire spatial pattern of neuronal assemblies and relations between them.

³² The idea of a functional system, the network of localized brain centers, each one with specific lower functions, interacting dynamically in complex psychological activities, was developed first by Vygotsky [216] and then by Leontiev [217].

³³ Metastability is well known in physics, however in relation to neural system it was first identified by Kelso [219] and was formulated within a classical model of coordination dynamics called the extended HKB [220] (HKB stands for Haken, Kelso and Bunz [221]). Metastability, by reducing the strong hierarchical coupling between the parts of a complex system while allowing them to retain their individuality leads to a looser, more secure, more flexible form of function that can promote the creation of new information [3]. Later, metastability has been acclaimed as the new principle of brain functioning [222].

³⁴ The term “field” is used here in exactly the same way as in physical science and denotes any continuous mathematical function of time and location, in this case the number densities of active neuronal assemblies in each cortical tissue mass. Defined in this manner, the existence of these fields is non-controversial [224]. The short-time modulations of these field variables are believed to be directly related to cortical or scalp recorded EEG [192].

electrodes that were spaced at 0.5 mm. Interestingly, in these experiments information concerning the identity of a particular odor was carried not so much by the *temporal* shape of any particular EEG wave but by the *spatial* pattern of EEG amplitude (the contour plot) across the entire surface of the olfactory bulb [26].

An EEG signal is composed from natural frequencies (oscillatory activity) [149], which are traditionally divided into delta (1-3 Hz), theta (4-6 Hz), alpha (7-13 Hz), beta (15-25 Hz) and gamma (35-45 Hz) frequency bands (see Fig. 6). These basic EEG bands are assumed to reflect different functional processes in the brain [22,232-234]. EEG oscillations have been intensively studied over the past years [24,27,235-246]. As a result of this research, it is suggested that the oscillatory activity of neuronal assemblies reflected in characteristic EEG rhythms constitutes a mechanism by which the brain can regulate changes of a state in selected neuronal networks to cause qualitative transitions between modes of information processing [247]. For example, it has been shown that fast oscillatory activity during sleep facilitates information flow from the hippocampus to the neocortex, while theta rhythm supports information transfer in the opposite direction: from neocortex to the hippocampus [248]. During wakefulness low-band alpha mainly related to the subject's global attentional readiness, whereas high-band alpha reflects the engagement of specific neural channels for the elaboration of sensorimotor or semantic information [237]. Additionally it was shown that beta oscillations are able to synchronize neural populations over long conduction delays [249] and might be suitable for the functional coupling of remotely distributed brain regions. Further, oscillatory gamma responses were shown to be involved in visual perception and cognitive integrative function [250]. It is well established that EEG rhythms can modulate the excitability of neuronal cells changing the probability of their firing or dragging them into synchrony, hence influencing the coding of information [251]. Thus, different oscillatory patterns may be indicative of different information processing states; and it has been shown that the oscillatory patterns play an active role in these states [252,253].

Moreover, it has been proposed that brain oscillatory systems act as possible communication networks with functional relationships to the integrative brain functions [254]. This proposition is based on the fact that in an electric system optimal transmission of signals is reached when subsystems are tuned to the same frequency range. As it has been reviewed above, the brain network is based on short- and long-range interactions between different brain systems (and/or modules) which oscillate at frequencies that are coherent and specific and, thus, capable of

resonance³⁵ – communications [153]. Indeed, the empirical results demonstrated that selectively distributed brain oscillatory networks (producing EEG delta, theta, alpha, beta, and gamma frequencies) constitute and govern mathematically the general transfer functions of the brain. The transfer function, represented mathematically by frequency characteristics or wavelets, constitute the main framework for signal processing and communication [256]. The existence of general transfer functions in the EEG is interpreted as the existence of distributed networks in the brain having similar frequency characteristics facilitating or optimizing the signal transmission in resonant frequency channels³⁶. Using this mechanism the brain determines who talks to whom at any particular moment. In this sense, the brain can rewire itself dynamically and functionally on a time scale of milliseconds without changing the synaptic hardware [157] and represent complex brain functions by the superposition of various oscillations in the frequency ranges of the EEG.

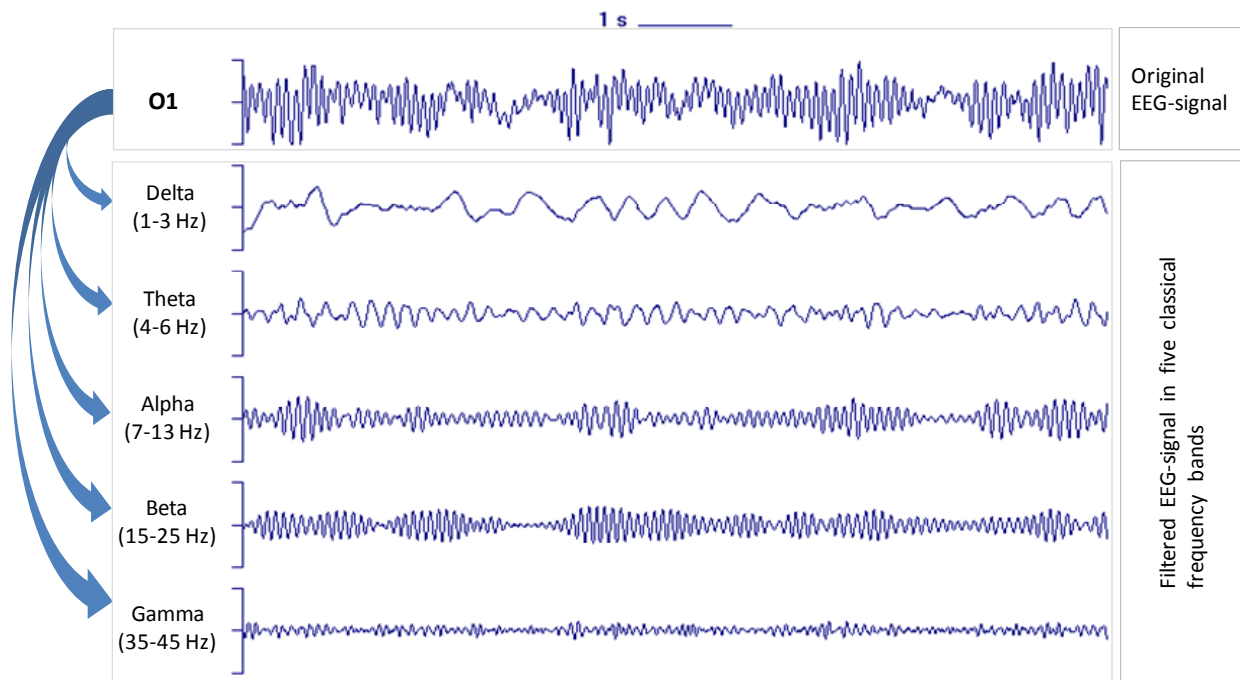


Figure 6. Composition of the EEG signal from different frequencies (oscillatory activities). Five classical physiological bands are shown for the same raw EEG signal: delta (1-3 Hz); theta (4-6 Hz); alpha (7-13 Hz); beta (15-25 Hz); and gamma (35-45 Hz). These basic EEG bands are assumed to reflect different functional processes in the brain.

³⁵ Resonance – a system which is characterized by its own oscillation frequency and can enter into vibration if stimulated (subjected to sound waves, electromagnetic waves, or mechanical vibrations according to the nature of the system) by frequencies close to those peculiar to the system itself [255].

³⁶ It is important to note that neither presynaptic nor postsynaptic neurons “choose” their frequencies “at will”. Instead, the frequencies are determined by the intrinsic properties of the neurons and the overall activity of the brain.

Observations of EEG signal show that it is characterized by the more or less stable (quasi-stationary) episodes and sudden changes in amplitude [226,257,258], frequency [243,244] and phase [259-262]. Such abrupt changes in one or several of these EEG characteristics (amplitude, frequency or phase) mark a brief state of indeterminacy – transition (we will return to this in Section 4.2). It has been shown that the quasi-stationary periods vary from ~30 ms to 6 sec depending on the EEG characteristic and the type of brain operation. Kaplan [263] and Freeman [195] called such quasi-stationary periods “frames”. John [264] proposed a mechanism, according to which a cascade of momentary “perceptual frames” converges on cortical “functional frames” to establish a steady-state perturbation (*spatial-temporal signature*) from baseline brain activity [265]. This mechanism has received substantial support from EEG studies: Research by Lehmann and colleagues [266,267] has demonstrated that the dynamics of the brain unified EEG field is represented by the intervals of quasi-stability (or “microstates”) and by sudden transitions between them [268,269]. Furthermore, their studies have shown that these microstates are associated with different modes of spontaneous thoughts [270] or with spontaneous visual imagery, or abstract thinking [271].

According to the metastable principle, described above, EEG signals produced by local and autonomous neuronal assemblies should also be dynamically synchronized among each other, thus shaping large-scale functional connectivity [38,272], which supports cognition and eventually consciousness [30,222].

2.3.3. EEG functional connectivity

EEG synchronization³⁷ reflects (and promotes) functional connectivity between two or more cortical areas [275]. Formally, two or more neuronal assemblies are functionally connected if the temporal correlation between the neural activity (e.g., measured by EEG) of the assemblies is greater than a certain threshold [276]. The idea that synchrony of EEG potentials reflects neural connectivity has been proven in a direct experiment carried out by Livanov [277]. In this experiment the correlation coefficient between EEGs in visual and motor cortical areas of the rabbit was estimated. It appeared that, if the correlation coefficient exceeded a particular level, the visual

³⁷ The initial idea of brain potential synchrony as a main mechanism for neuronal communications descends from basic research of the Russian classic neurophysiological school of Vvedensky [273] and Ukhtomsky [274]. At the beginning of the XXth century they postulated that the frequency cycle per time unit is a fundamental parameter, which characterizes the neural structure functional state (the “functional lability” parameter). Ukhtomsky [274] proposed that the coincidence of the functional labilities of two structures promotes their functional connections.

signal triggered paw movements, and if this coefficient was lower than the established level, no motor reaction occurred.

Studies have shown a relation between the size and distance of an interaction and the frequency of synchronization: The larger the neuronal assemblies involved, the lower the frequency in which activity in the assemblies gets synchronized [225]. A theoretical framework for an inverse relation between frequency of activity and spatial scale of a network has been given by Nunez [172]. According to experimental results, however, the neuronal assembly is not defined on anatomical grounds but rather is recruited functionally according to the cognitive task.

Recent analysis has revealed that brain functional connectivity networks have the small-world properties of dense local connectivity between neighboring structures³⁸, i.e., high clustering, and a short path length between any two structures [279-281]. Such type of functional structure is sparse (i.e., all areas are not directly connected to one another). Additionally, the new characteristics of large-scale brain functional connectivity, such as scale-free properties have also been revealed recently [282]. Apparently, the loss of both small-world and scale-free characteristics has been linked to various brain disorders [283-285], suggesting that these properties of functional connectivity are important for brain operation. For example, it was shown that networks with small-world characteristics are able to process information efficiently at both local and global levels [286], give rise to a fast system response with coherent oscillations [287], promote synchronized oscillations [288], allow both functional specialization and global integration, and maintain low wiring costs [281]. It is speculated that exactly these advantages might be the reasons for why these small-world and scale-free characteristics have evolved in the brain during the course of evolution [278].

The guiding concept in this subsection is that the active states of functionally connected local EEGs are selectively structured in three key dimensions [78]. First, they are *spatially* structured by the combined activation of discrete, local cortical (and indirectly subcortical) neuronal assemblies. Second, they are *temporally* structured by the changing combinatorial arrangement of active assemblies during the expression of cognitive functions [191]. Finally, they are coordinatively (*spatio-temporally*) structured by the specifically patterned joint actions of synchronized assemblies [25,30,222] (see also [3,22]). This view is reminiscent of Ukhtomsky's principle of *dominanta*³⁹

³⁸ It is worth mentioning that these small-world characteristics have been discovered in brain networks at all scales, down to networks of individual neurons [278].

³⁹ The *dominanta* is characterized by the following *global* properties [274]: (a) at any time instant, the nervous system has only one active, dominating constellation of co-excited neuronal assemblies characterized by a common rhythm and common action (behavior); (b) the same individual neuronal assemblies can be included in different dominant constellations; (c) the involvement in one constellation, or disassociation from it, is determined by the ability or inability of these neuronal assemblies to acquire the same tempo and rhythm of activity; (d) "traces" of the previous

which is, according to Ukhtomsky, the physiological basis of the act of attention and subject's thought [274]. We will turn to this later in Section 4; for now let us give one example: In an experiment aiming to study working memory it has been shown that functionally distant cortical regions were preferentially synchronized and involved in different short-term, chronologically ordered stages of memory processing such as encoding, retrieval, and retention [289]. Although memory encoding, retrieval, and retention often shared the same set of cortical regions, it is important to note that the specific functional integration (indexed by the operational synchrony) of these areas was unique for each stage of the memory task. An analogous principle was found in the audio-visual speech integration study [290].

The existence of hierarchy of spatial-temporal patterns embodied in and among neuronal assemblies is necessary but not sufficient to exhaustively describe the hierarchy of mental representations at the psychological level. In addition, it is crucial for the neural counterparts of mental representations to be stable⁴⁰ at least for some time [68]. This view is supported by the Grossberg position [111], who has emphasized that for a system to successfully adapt its behavior to an ever-changing environment, it must be not only plastic but also stable. The stability is an important part of the Perlovsky's convergent states of dynamic logic processes during which the internal representations of a system are getting more definite and crisp, and become fit to the input signals [73]. Thus, according to the concept of contextual emergence [298,299], Grossberg resonance [111] and Perlovsky convergent states [73], the condition of stability does not depend only on the neurobiological level. It also depends on features of mental representations at the

dominantas persist over long periods in the higher levels of the nervous system, and with complete or partial recovery of the initial conditions, they can completely or partially reappear. At the same time, the dominanta is characterized by the following five *local* properties [274]: (a) increased excitability; (b) stability of excitation, i.e., for excitation to produce any marked behavioral effect, it must not undergo rapid changes over time; (c) excitation summation, i.e. the ability to accumulate excitation not only from specific, but also from non-specific stimuli; (d) inertia, i.e., the ability to retain the state of excitation once the initial stimulus has ceased; (e) conjugate inhibition, i.e., the ability to exclude from the dominanta those neuronal assemblies whose activity is functionally incompatible with the activity of the dominanta constellation.

⁴⁰ The stability of spatial-temporal patterns of neural activity has been observed not only in the intact brain [291-293], but also in brain slices [294-296]. It has been shown that in cultured monolayer networks the observed patterns are stable over minutes of extracellular recording, occur throughout the culture's development, and have a temporal precision within milliseconds. According to researchers [296], the identification of these patterns in dissociated cultures and their persistence despite the topological and morphological rearrangements of cellular dissociation is further evidence that precisely timed patterns are a universal emergent feature of self-organizing neuronal networks. O'Brien and Opie [297] have defended the idea that phenomenal experience is caused by such stable patterns of neural activity in the brain. In other words, stable patterns of brain activity are both necessary and sufficient to produce phenomenal experience. Phenomenal consciousness, from this perspective, depends neither on specific mechanisms nor on specific brain regions, but emerges as a result of the stability of some representations at some particular point in time.

phenomenological level. In this sense, stability conditions for neuronal assemblies represent a contingent phenomenal context in addition to the neurobiological description [68].

In the next section we review in detail the spatial and temporal organization of the phenomenal level responsible for subjective awareness and consciousness.

3. Space and time in the mind

We would like to start this section with citation of Revonsuo [300], because he made the most detailed and systematic analysis of spatial-temporal organization of the phenomenal mind: "...there is every reason to believe that an understanding of the inner structure and dynamics of the phenomenal level might render the gap less unbridgeable, for the features of the phenomenal level (how it is structured, how it dynamically changes across time, and so on) offer top-down constraints for the science of consciousness in the search for potential explanatory mechanisms in the brain. Once we have a detailed description of the phenomenal level, it will suggest what sorts of lower-level neural phenomena might be closely associated with the higher phenomenal level, even if such phenomena would not yet have been discovered by neuroscience." Indeed, it makes sense to search for the lower level of explanatory mechanisms (neurophysiology) only after there is a clear description of the phenomenon (phenomenal consciousness) that these mechanisms are supposed to explain.

Before we will go on to elaborate the spatial-temporal organization of phenomenality, it might be useful to clarify our usage of the term "phenomenal consciousness". Literally, *phenomenology* refers to "phenomena": appearances of things, or things as they appear in our experience, or the ways we experience things [301]. As to consciousness, then it is a commonplace for this term to have a number of different connotations that relate to different levels of the phenomenon description. For example Penrose [302] speaks about algorithmic nature of consciousness, while Chalmers [303] interprets consciousness as some kind of information, which is present in all sorts of physical systems. Yet some researchers relate consciousness to physical phenomena at the quantum level [304-306], or to specific receptors at the neurons [307], or even to specific types of neurons, which are very different from the remaining neuronal cells [308]. Others relate consciousness to a coherent activity of large neuronal populations [112,309] or to particular neuronal pathways [310]. Finally, some researchers associate consciousness with the whole organism-environment interaction [311,312]. However, none of these interpretations takes a subjective (phenomenal) experience seriously in its own terms. The proper definition of

phenomenal consciousness should address the phenomenal level *itself* rather than reduce it to some other phenomenon, distort it or even eliminate it altogether.

In context of the aforesaid we support the notion⁴¹, according to which phenomenal consciousness refers to a higher level of organization in the brain⁴² and captures all immediate and undeniable (from the first-person perspective) phenomena of subjective experiences (concerning hearing, seeing, touching, feeling, embodiment, moving, and thinking) that present to any person right now (*subjective present*) and right here (*subjective space*) [4]. In this definition the phenomenal means subjective: Someone possesses phenomenal consciousness if there is any type of subjective experiences that is currently present for him/her. Experimental and empirical studies had demonstrated that such phenomenal (virtual) world consists of the fine hierarchical spatial-temporal architecture, which we shall discuss below.

3.1. Phenomenal space

An important aspect of phenomenal consciousness is the ontological status of its spatial system called *phenomenal space* [324]. According to some researchers, the ontology of phenomenal space could be directly identified with external physical space [325-327]. The proponents of this view hold that physical objects themselves are perceived “directly.” That is, what one immediately perceives is the physical object itself (or a part of it); thus there is no problem about inferring the existence of such objects from the contents of one’s perception. However, since the “phenomenal objects” subjectively present in one’s mind are the end result of a long causal chain of probability (statistical) events⁴³ happening at different levels of the neuronal system, this view no longer holds true [324]. Indeed, for us as subjects, the reality with which we are directly in touch is necessarily

⁴¹ Any definition of the concept of consciousness is bound to be controversial. We are not claiming that the definition which we use is the only way of defining consciousness. This definition, however, respects the phenomenon itself as we experience it (from the first-person perspective) and it is quite useful for empirical science.

⁴² Here we mainly follow the ideas of Revonsuo [72]. The approach formulated by Revonsuo relates to Biological Realism (a variety of scientific realism) that directly studies the interface between neural and mental phenomena. This approach has several assumptions: (a) consciousness exists in its own right; it is separate from other cognitive functions and can be independent from external reality (dream experience, [313-315]) and thus should be studied as an independent variable (for the argumentation, see [316]) in its own terms, (b) it is a natural phenomenon, (c) it has some causal powers distinct from purely neurophysiological (non-phenomenal) realm; recent neuroimaging [317] and cognitive studies have demonstrated that mental processes or events do exert “downward” causal influence on brain plasticity and the various levels of brain functioning (see also [318-320]) and that the conceptual representation of an ambiguous perceptual stimulus biases sensory processing [321-323], and (d) it ontologically depends on brain – the spatial location of the mental phenomenon in the natural world.

⁴³ It should be made clear, that these events are totally outside the consciousness domain: They are either nonconscious entities in the external world (not in the organism), or they are nonconscious biological (neurophysiological) events inside the organism (and/or brain) [72,328]. Consciousness may causally dependent on them, but it does not depend on them ontologically – it can in principle exist in the absence of them (i.e. dream experiences, [313-315] or sensorial deprivation).

our “inner” phenomenal reality and could not be anything else [72]. If it is so, then the phenomenal consciousness could have its own phenomenal space. The existence of independent phenomenal space is nowadays well confirmed by neurophysiological and cognitive investigations [329-332]. As it was pointed by Smythies [333] this phenomenal space may be identical with some aspect of brain space but not with any aspect of external physical space. The same idea was explicitly formulated by Searle [334]: “The brain creates a body image, and pains, like all bodily sensations, are parts of the body image. The pain-in-the-foot is literally in the physical space of the brain.” Another researcher, Kuhlenbeck [335] made an even stronger claim, suggesting that “...physical events and mental events occur in different space-time systems which have no dimensions in common.”

What is this phenomenal space about? According to a conceptual point of view, it is the most fundamental ingredient of phenomenality of a mind: A unifying spatial 3D coordinate system⁴⁴ in which all phenomenal contents (hearing, seeing, touching, feeling, embodiment, moving, and thinking, etc., including ‘self’) must be embedded in order to be directly present in someone’s subjective experience [72,337-339]. The psychology literature offers compelling evidence that such volumetric subjective space is readily available in the mind [340-342] (see also below). So does our everyday subjective experience. It has been suggested that this phenomenal space in which all experiences take place forms a bridge between nonconscious biological mechanisms and phenomenal consciousness [72]. It has also been suggested that at present there is no empirical support for this hypothesis and this should be a matter of future research. What should be noted, however, is that this supposition offers a plausible interpretation from the first-person perspective: The pure phenomenal space – just an empty 3D matrix – resides at the level of brain organization that is ontologically *subphenomenal* (we never experience *subjectively* the contentless coordinate system as such directly; we could know about it only through the relations among phenomenal

⁴⁴ Revonsuo calls this spatial coordinate system the “virtual space” [72]. This virtual space is the unifying framework that is responsible for global unity of consciousness. In Revonsuo’s words [72] “It explains why there is at any *one* time exactly *one* world-*for-me* in which all my phenomenal experiences occur in a fundamentally interrelated fashion” (p. xxi). Even in a pathological condition known as multiple personality disorder (or dissociative identity disorder) this principle is not violated: At each given time only one amongst the multiple identities can express itself [328]. The term “virtuality” is used here in the same way as in the computer engineered “virtual reality” [336]. A virtual reality is a computer-generated world simulation, in which the subject is immersed, that does not exist as a world anywhere inside the computer or even in the program. This is exactly the same with phenomenal world which could not be found in the brain’s anatomy. Phenomenal space is thus “virtual” for precisely the same reason: It provides complete *immersion* for the embodied subject in the middle of a perceptual (virtual) world where he/she is surrounded by patterns, objects, people and events.

objects)⁴⁵. In Section 4 we will describe the potential neurophysiological candidate for this subphenomenal space.

Careful experimental studies have revealed that different phenomenal features (qualia⁴⁶) can be discriminated from each other on the basis of their spatial location within the single matrix of phenomenal field [344]. For example, it has been shown that all experienced objects (including people) are always located in a certain direction and distance in relation to the centre of this phenomenal space. One line of supporting experimental evidence for this comes from studies on the topography of meanings of the phenomenal objects [345-348]: In these studies the semantical analysis of individual connotations was conducted by means of semantical differential (SD)⁴⁷. Furthermore, it was experimentally found that our subjective (phenomenal) visual space/field is structured from at least two major parts: focal awareness (attended) and peripheral awareness (outside attention) [349]. Moreover, it was shown that even the preattentive peripheral field is also divided into subregions (through the figure-ground grouping processes) [350]. The same is true not only for the visual patterns and/or objects but also for the auditory and any other sensorial features (or qualia) [351]. Importantly, it was experimentally found [352-354] that the phenomenal fields of different modalities (for example, visual and auditory) are spatially and temporally integrated, so that the different features belonging to the *same object* are realized in the *same location and time* (for temporal aspects, see the following Subsection). This ability allows us not only to see the shape of an object, we are also immediately aware of its position in relation to our own body and to other objects in the scene⁴⁸.

An additional line of evidence for the existence of phenomenal space comes from dream studies. These studies have special importance for consciousness research, because they reveal phenomenal consciousness (dream “world”) in a pure form isolated from the usual external sensory input and motor output [314]. Considerable empirical findings clearly indicate that dream phenomenal experiences⁴⁹ are carefully organized within a spatially extended world or virtual

⁴⁵ Damasio [328] using findings from experimental and clinical neuropsychology and neurophysiology comes to conclusion that this phenomenal space is not self-presenting as such; however it is the crucial aspect that allows self-presenting qualities (contents) to come into being.

⁴⁶ Quale (plural “qualia”) is the qualitative identity of the subjective experience. The concept was first defined by Lewis [343] as the qualitative character of “the given” something which is present in a subjective experience.

⁴⁷ SD is the semantic analysis of connotations of concrete and abstract objects/ideas based on the calculation of distances between them within a phenomenal space [345]. It has been shown that the basic topographical structure of such connotations (semantic relations) is identical in different cultures, in people with different education and even in people with a psychopathological condition, when compared with healthy subjects [346-348].

⁴⁸ Patients with simultanagnosia can recognize objects, but they cannot point at them or describe where they are located in space. Moreover, if shown more than one object at a time, such patients report seeing only one [355].

⁴⁹ Even individuals who are blinded after the age of 5–7 years appear to have visual imagination and full-fledged dreams with completely realistic visual imagery throughout their life [356], thus indicating the existence of a quite independent and rich phenomenal world.

reality [314,357-360], which in 90% of dreams is experienced as a reality, not as a dream or as a hallucination [361,362].

Interesting evidence about the presence of independent phenomenal space was obtained in patients with hemispatial neglect [363,364]. Patients with this pathology experience spatially extended scenes and objects only in one half of the space of a healthy person. Moreover, the patients' actions are similarly restricted toward stimuli in one half of space. For example, the neglect patient may eat food only from the one side of the plate, may dress only one side of the body and so on. Interestingly these patients do not experience any “missing space”: they are just not aware of the fact that their phenomenal space represents only one half of the real physical world [365]. At the same time experiments show that in such patients visually presented objects can still be fully processed in the brain, but outside of consciousness [332].

Another important feature of a phenomenal space 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 [72]. Such egocentric reference frame or the first-person perspective was called *perspectivalness*: It possesses a focus of experience, a point of view [366]. Converging evidence for this centeredness (first-person perspective) comes from a number of sources. First, in our everyday thinking we locate our “self” within the boundaries of our body image in the centre of a perceived world⁵⁰. Second, even in such psychopathological condition as an “out-of-body” experience, in which patients claim to experience themselves in two places at once [368-370], accurate analysis of reports reveals that at any *one* time the phenomenal world is seen either from the embodied or the disembodied perspective, which is still the centre of the phenomenal world. The analogous evidence comes from patients with multiple personalities: In each given moment only one self is expressed within one unified phenomenal space [328]. Third, in dreams the dreamer appears in the centre of a spatially extended phenomenal world and interacts with the surrounding dream environment [314,357-360]. Based on these findings it has been concluded that this centeredness feature is very important, since it allows us to engage in effective behavior within the local environment or plan our future actions. Indeed, in order to do so, we must have some internal representation of the actual and possible spatial relationships between our self and other significant objects in the veridical space [367].

⁵⁰ Subjectively, we experience our own self (the so-called observing ego) as residing in the centre of a phenomenal spatial world – this is what gives the name to the egocentric reference frame. According to this view, whenever the centered Self moves, it changes its position in relation to every phenomenal object in the phenomenal world, but it never changes its relation to the centre of phenomenal space [72,367].

The phenomenal contents⁵¹, such as different patterns or simple and complex objects, scenes, or even self, which we experience as being directly present for us in physical space, are never *experienced* as representations; they are purely experiential phenomena which are located within the phenomenal space. Neurophilosopher Metzinger [371] brought the term “transparency” to characterize this phenomenon⁵². According to this view, the phenomenal contents subjectively experienced are fully transparent, meaning that they give only the impression of being actual patterns, objects or scenes out there in the physical world rather than some sort of *transparent surrogates* (or virtual simulations) of these things in the physical world that they are representative of [373]. The system (brain and consequently the subject) cannot distinguish the surrogate of the object from the object itself; it just “looks through” the surrogate as if it is the real physical object itself in the world⁵³ [375-379]. Thus, the whole phenomenal world (space together with contents) is a transparent surrogate of the physical world somehow realized in the brain.

We should point out here that subjective experience is far from being a kaleidoscope of chaotic patterns of phenomenal features. Most of these patterns are carefully and hierarchically organized, forming phenomenal objects, images, or multimodal scenes of different complexity, all in the context of the entire matrix of phenomenal space. In other words, the higher-level phenomenal entities are based on the complex organization of lower-level phenomenal entities [378,380] (Fig. 7). At the bottom of such self-organized hierarchy there are *phenomenal features* (qualities), which instantiate simple phenomenal contents (sounds, colors, touches, emotions, tastes, smells, and so on). They are the identity, the “stuff” that experiences per se are made of [72]. Such phenomenal features are carefully organized into *patterns of qualities* to make up the patterns of experiences. The next level of phenomenal space is represented by *phenomenal objects* (with their Gestalt and semantic windows) [72]. Phenomenal objects can be described as complex patterns of qualities which are spatially extended and bounded with each other to form a unified item (Gestalt window⁵⁴) with a particular meaningful categorization (semantic window) immediately present subjectively for the subject. Any such object can be further organized hierarchically into parts (or features) of a

⁵¹ The content of consciousness is any pattern of phenomenal experience, such as a pattern of sensations, perceptions, mental images, emotions (and other) or any combination of them.

⁵² Lotze [372] was probably the first who explicitly formulated the problem that the nervous system cannot see the anatomical layout of its own wiring and thus cannot see its own processing. He called this problem the “local sign”. In modern formulation the local sign problem is referred to as transparency.

⁵³ One good example illustrating this kind of phenomenon was brought by Smythies [374]. In this thought experiment, when we watch a live broadcast of a football game on color TV, we see the game itself, not a complex arrangement of patterns on the TV screen. Here the screen is perfectly transparent for our perception: what we see are the events going on the football field, not the physical events on the TV screen.

⁵⁴ According to Gestalt psychologists, the perceived environment is pervasively clumpy [381]: At various scales and levels of abstraction, things that belong to the same category tend to be found close together and also tend to be more similar to one another than do things that belong to different categories [382].

more complex object, or on the contrary decomposed, where all of the components can be realized as separate simpler virtual objects independent of each other and with their own Gestalt and semantic windows (for a similar view about mental objects see [186]). As a consequence, the 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 [4]. The potential neural mechanism of this phenomenal hierarchy will be presented in Section 4; the mathematical formulation of some aspects of it can be found in [73-75,93].

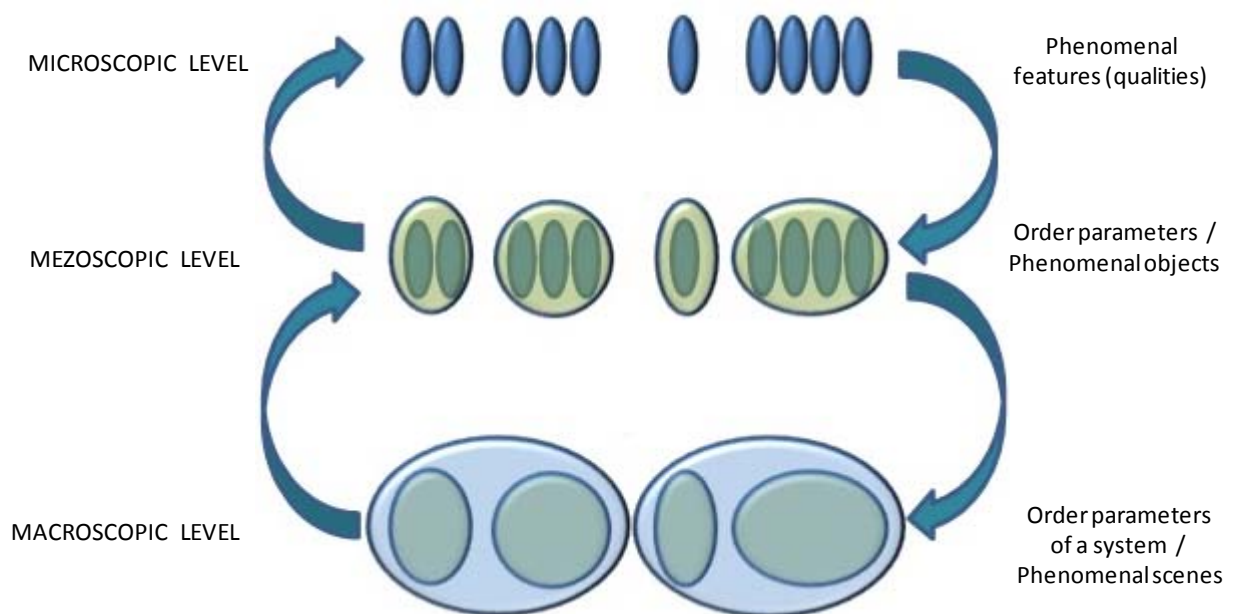


Figure 7. The hierarchy of subjective (phenomenal) experience (reinterpretation of Fig. 1). In this hierarchy the higher-level phenomenal entities are based on complex organization of lower-level phenomenal entities all the way up to the most complex phenomenal scenes and/or subjective world.

Several phenomenal qualities or objects that share the same phenomenal space and interrelate between one another must be present at the *same time* (see for a review [339]). This implies temporal presence: Subjective experience comes into existence at some point in time and it ceases to exist at some later point. These temporal aspects of phenomenality are reviewed in the following Subsection.

3.2. Phenomenal time

Temporal dimension is another extremely important aspect of phenomenality of the mind. Indeed, any phenomenal experience has temporal duration: There is some moment in time at which an experience emerged, before which it did not exist yet, then it lasts for a certain period of time and after that disappears [72]. Therefore, the phenomenal patterns, objects and/or scenes never stop – they are in constant flux. According to James [383], phenomenal consciousness is dynamic in that it continually moves from one relatively stable part (the resting place) to another relatively stable part, and these stable parts are separated by abrupt transitive parts (for modern interpretations see [26,38,50,55,71,384,385]).

However, subjectively we directly perceive only the inner phenomenal presence, related to an undeniable ‘now’ [54,371]. The subjective arrow of time emerges as the result of intro- or prospection, when past or future is (re)constructed mentally [386]. The subjective ‘*sense of presence*’ can be defined as a temporal framework during which all immediate interrelated and bounded experiences (transparent surrogates) take place and directly present to a subject right now [72,387]. During this ‘presence’ period an a priori form-as-potentiality (fuzzy mental content) becomes a form-as-actuality (a concept)⁵⁵ [388]. In the words of Brown [66] “the becoming is absorbed into the present and obscured by the wholeness of the entity it creates”. Russell [389] described it in the following way: “An entity is said to be now if it is simultaneous with what is present to me, i.e., with this, where ‘this’ is the proper name of an object of sensation of which I am aware” (p. 213). According to Smythies [324], “the experienced ‘now’ of time is where consciousness, or the experiencing subject, is...” In a similar way Alexander [390] stated that “...the present being a moment of physical Time fixed by relation to an observing mind”. Varela [67] described such moments of consciousness as dense moments of synthesis in the stream of consciousness, in which specific contents appear in an uncompressible duration. To characterize this phenomenon, Metzinger [371] introduces the notion of *mental presentation*, which is the subjective window of presence.

The scientific quest is to explain these temporal features of subjective phenomenality in terms of an adequate neurophysiological mechanisms and proper mathematical formulations. Even though

⁵⁵ Generally, a distinguished “present” associated with the transition from potentiality to facts [55]. According to this view, the temporal width of the present depends on the specific event which is taking place until it becomes a fact. The becoming is not apprehended because there are no objects to be aware of until change is completed [66]. Indeed, we feel the duration of ‘now’ as a line in time, yet we are unaware that the perceptual contents within this duration are replicates that actualize over phases. Therefore, the extended present is marked by a loss of sequentiality: It is impossible to attribute a sequential order to events within this extended present [55]. As a result, the duration of the present is felt, but it is virtual [66].

future research will have to address these mechanisms in detail, in Section 4 we will describe one of such potential mechanisms.

Experimental results have shown that there exists a particular time interval of ~70-100 ms that is the minimum time required for the phenomenal binding of sensory inputs into a single event [75,391-393]. This minimum time interval has several names: as the mental “quanta of time” [394,395], “perceptual moment” [396], or “perceptual frame” [397]. Many psychophysical observations have been made about such discrete phenomenal processes. For example, it was experimentally 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 [398-400]. This phenomenon is compatible with the idea of a discrete perceptual “frame” of ~100 ms or less within which stimuli would be grouped and subjectively interpreted as a single event. Other findings addressed the periodicity in reaction time [401,402], the periodicity in visual threshold [403] and the perceived causality [404]. Experiments of Pöppel [65,405,406] have also argued for the existence of a temporal integration span interval. For a detailed review of these psychophysical observations see the relatively recent work of VanRullen and Koch [407].

Another kind of support for the experienced “now” came from neurophysiological research. For example, if two different objects or images are presented to the two eyes, either they are merged into one, if coherent enough (binocular fusion) [408], or only one of them will be seen at any one time (binocular rivalry) [409]. The same ever-present temporal integration span is responsible for the binding of different features (color, texture, luminance and so on) of the same object (*feature binding*)⁵⁶ and for the binding of several distinct parts of complex objects or scenes (*part binding*)⁵⁷ together [412].

The phenomenal present moments also develop over time in the form of ever-moving ‘now’⁵⁸, thus integrating past and future [54,371,414,415]. One important temporal characteristic of phenomenal experiences is that they are constructed and updated extremely rapidly [416,417]. For example, we are able of recognizing and understanding complex images of scenery flashed briefly

⁵⁶ Patients with Balint’s syndrome do not see the object with all its features coherently bound together. Moreover, they usually miscombine the features from different objects within the same object [410].

⁵⁷ Patients with prosopagnosia (the inability to recognize faces) can usually see the mouth, eyes, nose and other parts of the face, but they are not bound into a structured unified face [411].

⁵⁸ In some sense, as was proposed by Alyushin [413], a psychological presence resembles a movie frame. It is discrete, and in terms of the whole process nothing happens within it; everything happens only in the sequence of frames. Further, he explains the well-known phenomena of varying speed of subjective time: “In terms of the temporal frames conception, when the frame duration gets two times shorter, there are twice as many frames managing to sequence each other in the brain within a second. Thus, the density of the frame flow doubles. What rises is the absolute volume of the incoming subjective information. It is this overflow that is commonly described as acceleration of subjective time, and, respectively, deceleration of the outer time” [413].

around only 100 ms [418]. In everyday life if we turn our eyes or head very rapidly, our phenomenal experience is instantly updated to accommodate the new perspective. Thus, the temporal resolution of phenomenal consciousness should be extremely high: It can completely reorganize itself 3 to 10 times per second [72]. At the same time, the unification of phenomenal experiences between successive temporal frames is also important: Without the ability to retain phenomenal experiences of earlier objects and unite them with currently phenomenally presented objects, most complex mental (cognitive) operations would simply be impossible. For example, the only bits of language that one would be able to understand, in this case, would be single words; even the simplest of sentences is an entity spread over time [419].

Analysis of dream contents can reveal additional information about phenomenal time. For example, one form of dream bizarreness is presented by so-called ‘discontinuities’, which are the dream elements (objects, people or places) that unexpectedly appear, disappear, or are transformed along the dream timeline [420]. Analysis of such dream features leads researchers to conclude that the brain has difficulties in tracking through time the phenomenal features that belong to a certain location if that location is not constantly attended to [421].

The phenomenal “now” is also related to a known subjective phenomenon of timelessness, which can occur during near-death experiences, during intense suffering and emotions, violence and danger, altered states of consciousness, concentration and meditation, and shock [422-425]. During the experience of timelessness the subjective present either gets longer and longer or, on the contrary, individual subjective time units become so small that they get subjectively fused into one [426]. In either case patients subjectively experience that time stops. Related phenomena show an opposite tendency, when the temporal ‘now’ units get smaller but do not reach a fusing state: In this case patients (with schizophrenia or some other psycho-neuropathology) report the experience of accelerated flow of time [427,428]. Another interesting subjective temporal phenomenon registered in psychiatric patients reveals the existence of subjective backward temporal flow [427-429] (see Dennett [430] for a discussion of these cases). Some of these phenomena are difficult to explain rationally or to model mathematically, however future theoretical developments and scientific research will bring more light and eventually explain them. In Section 4 we will try to explain at least some of them.

Based on what we have described above, we may conclude that the phenomenal (or virtual) objects are carefully *organized hierarchy of patterns* of self-presenting phenomenal features. Such phenomenal world, as a momentary subjective (virtual) reality, is the total organization of *simultaneously present* phenomenal features (the complex global bundle), while the dynamics in

this phenomenal world is expressed through the succession of this complex global bundle – both instantiating the *phenomenal space-time* (PST) [72,339,431].

However, to explain the complementary features of consciousness such as *phenomenal unity* and continuity together with a *succession of discrete thoughts* and images, a reference to mechanisms outside the phenomenal realm is necessary [300]. Following Revonsuo [72] we could say 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.

The next Section reviews Operational Architectonics theory of brain and mind functioning, which integrates space-time descriptions of brain and mind from Section 2 and 3 within a unified theoretical and methodological framework.

4. Integration of space-time of brain and mind through unified operational space-time

These days the impressive amounts of empirical evidence (ranging from the molecular level up to large-scale functioning of the brain) being reported in brain research contrasts with the lack of theoretical frameworks for representing phenomenal space and time of a mind in terms of patterns of brain activity, and in general for comprehending brain cognitive functioning. We are now in a position to delineate a conceptual framework through which we can comprehend how disparate microscopic events at the neurophysiological level lead to the macroscopic organized patterns of synchronized neuronal activity, which parallel in a causal manner the patterns of phenomenal consciousness of different complexity during normal and pathological conditions. As reflected from this review, efforts are needed to combine, in a coherent way, the integration between the different levels of brain-mind organization: local and collective, neuronal and subjective, all originated through the spatio-temporal patterns of brain-mind activity.

Among the different methodological strategies adopted to study and to describe the brain-mind interaction and its expression in the complexity of brain activity, the so-called “Operational Architectonics” (OA) framework⁵⁹ [4,25,30,222,258,451,452] has some advantage because of its

⁵⁹ The initial idea concerning frame architecture of brain information processing has been independently proposed by several researchers: John [264], Barsalou [432], Kaplan [263], Sacks [433], and Freeman [195]. Later this general framework was used mostly as an “umbrella” notion in a series of experimental studies [257,289,290,434-450] leading to the accumulation of an enormous amount of empirical neurophysiological data which have permitted to extensively develop, broaden, and modify the whole conception and establish OA as a theoretical framework in its present form

compromise between simplicity, neurophysiological accuracy, and cognitive and phenomenal plausibility.

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 the EEG (and/or MEG) signal [226,461]) by examining topographic sharp transition processes (on the millisecond scale) in the EEG [25,30,222,258,451,452]. Detailed analysis of the complex structure and hierarchical architecture of EEG (see the following Subsections) reveals the existence of particular *operational space-time* (OST) which literally resides within the brain *internal physical space-time* (IPST⁶⁰) and is functionally isomorphic⁶¹ to the *phenomenal space-time* (PST). As we propose elsewhere [4], OST constitutes the neurophysiological basis of mind phenomenal architecture (PST), which was described in the previous Section. However, we do not subjectively experience these postulated causal relations that connect the OST (located in IPST of the brain) with the consciousness contents presented in PST. What we experience is the end result of these causal relations – namely our own subjective (and transparent) sensations, images, and thoughts [72,339,371,378,388]. Below we will illustrate this functional isomorphism by relating the EEG structure with the structure of phenomenal consciousness.

[4,25,30,222,258,451,452]. Since then, it has been used to study (a) different brain conditions, such as cognitive tasks [453], memory execution [289,454], multi-sensory integration [290], sleep and drowsy states [440,455] and hypnosis [456]; (b) different pathological conditions, such as depression [457], opioid addiction [458], abstinence [459], schizophrenia [460]; and (c) pharmacological influence [257,447].

⁶⁰ IPST is the domain where physical space and time are implemented in the neurophysiological activity of the most complex life-system – the brain.

⁶¹ The issue of isomorphism is controversial and many theorists argue that isomorphism is not actually necessary (for review see [74]). In most of cases such views articulate the *first-order* isomorphism, according to which if there is some internal neural event that corresponds to our experience of, for example, a “square”, then there should be active neurons in the brain that are spatially arranged in the form of a square. It is well-known that this is not true. We speak here about *second-order* or *functional* isomorphism. By definition, two systems that are functionally isomorphic are, in virtue of this fact, different realizations of the same kind (for detailed discussion see [462]). In other words, two different functionally isomorphic systems bring about the same function that defines the kind. In mathematics, descriptions of two systems which differ only by irrelevant elements but leave the relevant well-defined functional structure invariant are called isomorphic [32]. This structural isomorphism is referred to as second-order resemblance [463,464]. In second-order resemblance, the requirement that representing vehicles share physical properties with their represented objects can be relaxed in favor of one in which the functional relations among a system of representing vehicles mirror the functional relations among their objects [465]. In other words, two systems can share a pattern of functional relations without sharing the physical properties upon which those relations depend. However, functional isomorphism is “visible” only at the level in which similarities between otherwise disparate realizations can be seen, and so it is at this level that we must look for laws ranging over them. As it was shown [4], the OA theory articulates the proper (adequate) level to study functional isomorphism between brain and mind functioning, because it describe a complex electromagnetic phenomenon in the brain which is consistently correlated and compatible with the complexity of phenomenal world. Specifically, it is a sufficient framework that provides a neurophysiological basis for instantiation of *discrete* conscious experiences without fundamentally violating the demand of conscious *continuity* of the subjective presence [452].

To avoid any possible misunderstanding, we should stress that the goal of this Section 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 spatial and temporal phenomena in the brain and mind. The analysis in this Section thus reviews extension of the OA framework by developing a unified account of physical-, operational- and phenomenal- *space-time* of brain-mind organization.

4.1. Operation as a concept which unifies space and time

Since “operation” is a greatly overused and variously defined concept, many researchers sometimes despair at it ever being meaningfully used. Two extreme descriptions are evident from summing up all that has been written about operation in cognitive science. On one end of the spectrum operation is depicted in terms of the symbol manipulations of a digital computer; on the other the operation is just a matter of implementing a function. We take the middle ground in defining and using operation for its explanatory power in brain-mind science.

Formally “operation” stands for the *process* (or series of acts/functions) that applied to an operand, yield a transform, and is limited in time [466]; and can be broadly defined as the *state of being in effect* [467]. This is so regardless of whether this process is conceptual/phenomenal or physical/biological. In fact, everything that can be represented by a process is an operation. Such a point of view provides a basis for the discussion of the relative complexity of operations, where there is always a more complex operation/operational act that subsumes the simpler ones [222,451]. These simpler operations may also have their own complex architectures. Understanding of the operation as a *process* lasting in time and considering its *combinatorial* (spatial) 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 assemblies in the brain.

Therefore, this notion is fundamental in bridging the gap between brain and mind: It is precisely by means of the notion of ‘operation’ 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 what mediates between them [4]. Indeed, both the material neurophysiological organization that characterizes the brain (see Section 2) and the informational order that characterizes phenomenal mind (see Section 3) necessarily involve such events as *operations* at their cores. Furthermore, an operation can be at the same time viewed as an *act* (a process) and an

object (a thing). This is so for the brain functional architectonics and for the mind phenomenal architecture's features, where brain/phenomenal patterns are both the processes and things [4].

Described features of operation are explicitly utilized in the OA framework, according to which the notion of 'operation' is central for perception, attention, intention, memory, action, and eventually consciousness [4,25,222,451]. We will now briefly sketch the hierarchy of brain-mind operations (detailed analysis will be provided in the following Subsections).

At the lowest level of brain-mind hierarchy the most basic elemental *physical* operations of the brain are expressed as operations of the neurons: These "blind" operations process the electric currents which arrive on neuron dendrites and transmit the resulting electrical current to other connected neurons using its axon (see Fig. 2). Such operations have a completely neurophysiological ontology and, according to Searle [334], have no mental/subjective ontology whatsoever, therefore they are *nonconscious*⁶². One level above physical operations of neurons is the matrix of transient functional neuronal assemblies, which can already support elemental *cognitive* operations (different attributes of objects, environmental scenes or mental images/thoughts), which have phenomenal/subjective ontology in addition to the neurophysiological one. Therefore such operations can be *conscious* or *unconscious*. The following, higher level of brain-mind hierarchy is constituted by the synchronized operations of several neuronal assemblies – integrated spatial-temporal patterns which present *complex macro-operations* responsible for the phenomenal unity of complex objects or scenes. At last, the integrated spatial-temporal patterns (being by themselves the result of synchronized operations produced by distributed and local transient assemblies) could be operationally synchronized between each other (on a new time scale), thus forming more abstract and more complex spatial-temporal patterns which constitute new and more *integrated phenomenal experience*. At this top level of abstractness (reflective consciousness) we already do not have direct access to the brain (physical) processes, and therefore this subjective (conscious) experience seems so strange and mysterious to us [25].

Below we will review the main properties of brain operational architectonics, describe their relation/isomorphism with the phenomenal properties of mind (described in Section 3), and indicate how they can be practically measured or estimated.

⁶² A level of neurophysiological organization in the brain that is incapable of directly changing the content of subjective experience is regarded as entirely *nonconscious*. By contrast *unconscious* neurophysiological phenomena have the capability to modulate and even change the phenomenal content of consciousness in highly organized and specific ways (for a discussion see [334,468]).

4.2. Quasi-stationary EEG segments as constituents of simple operations and phenomenal features

As it has been discussed in Section 2, 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 [26,265], they are expressed within local EEG signals in the form of quasi-stationary⁶³ segments, each of which representing the envelope of the amplitude modulation (so-called a “common mode” or a “wave packet” [193]) in the neuronal masses under the recording electrodes (Fig. 8). Even though the neurons that comprise an assembly under the electrode may be spatially intermixed with neurons in other neuronal assemblies responsible for different operations, they are naturally separated by different time-scales – EEG frequencies [8,149,154] (see Section 2 for discussion).

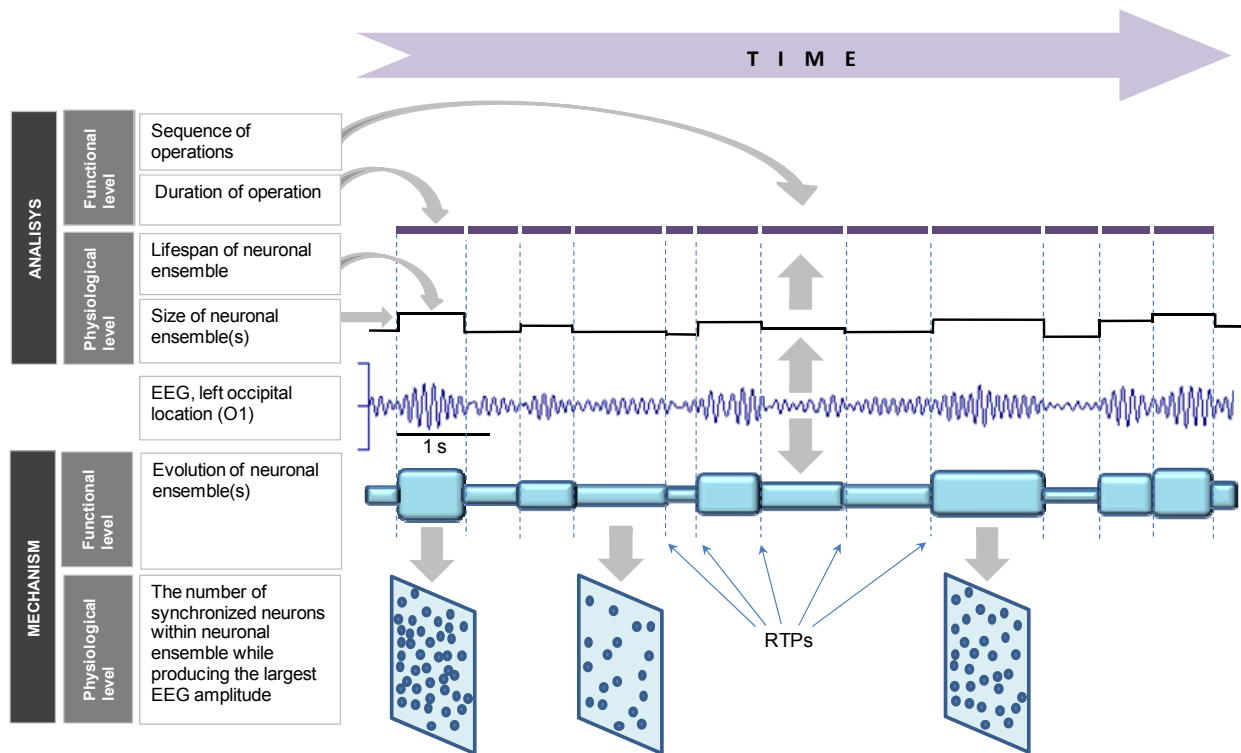


Figure 8. Schematic illustration of the neuronal assembly’s dynamic and its relation to a number of synchronized neurons and EEG signal. RTP – rapid transitional processes. EEG signal is filtered in alpha (7-13 Hz).

⁶³ Quasi-stationarity means nearly (or almost) stationary; whereas stationarity indicates stability of the studied parameter over time.

We argue that the network of neuronal assemblies in the brain together with their electromagnetic fields (indexed by EEG segments) may constitute the spatially organized subphenomenal matrix, which (as it has been discussed in Section 3) is “exactly the kind of entity that could help us to bridge the explanatory gap: it is in itself wholly non-phenomenal, yet it allows all the phenomeno-spatial organization to be manifested at the higher phenomenal level. It has one foot in the non-phenomenal realm, the other in the phenomenal realm” [300] (see also [72]). Let us explain. The cortical neurons themselves are highly distributed and intermixed and provide an internal structural analog of 3D space and time – some sort of coordinate matrix in the brain – which has no phenomenal functions whatsoever. The neurons are physical entities in the brain and their activity does not correlate reliably with cognition and levels of consciousness (as discussed in the Section 2). Therefore this neuronal net together with its neuropil⁶⁴ corresponds to the non-phenomenal realm of the subphenomenal matrix. On the contrary, the spatially and temporally structured electromagnetic field [23] produced by the functional and transient neuronal assemblies⁶⁵ is an appropriate candidate for the entity within which all operational and isomorphic (to them) phenomenal contents (including self) can be presented [4]. Therefore the local fields of transient functional neuronal assemblies are equivalent to operations which can be conscious (phenomenal). The basic feature of such coordinate matrix (coordinate system) is that each location (neuronal assembly) has the capability to realize a characteristic variety of local and dynamic electromagnetic fields corresponding to operations which instantiate self-presenting, qualitative features⁶⁶ and thereby can construct transparent phenomenal surrogates or virtual objects (for a discussion see Section 3). Therefore, this space-time matrix is regarded as the basis that mediates between the nonconscious (purely neurophysiological/neurophysical) and the conscious (phenomenal) domains.

Is it possible to prove these assertions? Clearly much of above discussion still needs extensive laboratory experimentation and theoretical clarification, but existing neurophysiological and neurocognitive research already provides some compelling evidence. For example, it has been reliably documented that the activity of individual neurons (a) cannot predict the dynamical patterns which would correlate with different cognitive and consciousness states [469]; (b) is imperfect and unreliable due to thermal fluctuations in the membranes of neurons’ trigger zones and their

⁶⁴ In neuroanatomy, a neuropil is a space between neuronal cell bodies in the gray matter of the brain. It consists of a dense tangle of axon terminals, dendrites and glial cell processes. It is where synaptic connections are formed between branches of axons and dendrites.

⁶⁵ For the difference between rigid anatomical (Hebbian) and transient functional neuronal assemblies see [25].

⁶⁶ One may see that operations of transient neuronal assemblies are functionally isomorphic with phenomenal features (qualities) (see Section 3). Indeed, it has been shown that a set of ‘feature extracting neural assemblies’ decompose in parallel the complex stimulus into so-called fragments of sensation: distinct neuronal assemblies have a preference to process distinct features (a preference for color, shape, motion, smell, etc.) [201,203].

biochemical nature [6]; (c) noncorrelated or only weakly correlated with cognition, behavior, and consciousness levels: For example, it tends to vary insignificantly in awake, sleeping, and anesthetized brains [112]. Hence, it is concluded that records of single-cells firing rates are not adequate in describing and explaining the phenomenal level, because we have no idea how they are supposed to contribute to the subjective phenomenology [31]. Anatomical neuronal nets (Hebbian assemblies) are also problematic for explaining the phenomenal features: (a) they are too rigid and very slow (because they rely on learning by repetition at a low-level, single neuron's organization) for our subjective perceptions which are fast and often unique [309,470] (see Section 3); (b) they have no flexible means of constructing higher-level operations by combining more elementary operations [186], hence, they are prone to the binding problem [187]. Therefore, Hebbian anatomical neuronal assemblies are also not adequate in explaining the phenomenal level.

By contrast, the transient (dynamic) functional neuronal assemblies are fast enough and have the required combinatorial power [25] to produce local bioelectric fields (of different complexity) corresponding to simple and complex operations with phenomenal content [4]. As we have already discussed above (and Section 2), such simple operations are reflected in the EEG quasi-stationary segments, which are in a way a standing waves within a 3D volume (see Fig. 8). 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 [258]). Moreover, it has been documented that different neuronal assemblies' local fields correlated with different conscious percepts [26,112] and that if cognitive processing does not take place, such transient neuronal assemblies do not appear [471]. 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 (for a similar view see [23]).

In this context, the *phenomenal space-time* (PST) is limited by 3D *operational space-time* (OST) which is at the level of electromagnetic fields, and which in its turn is partially determined by the 3D structural and dynamic properties of the brain *internal physical space-time* (IPST).

Treuhub [367] suggests that this IPST⁶⁷ is a topological analog of our natural *external physical space-time* (EPST). The structure, complexity and diversity of components of an OST (macrolevel field phenomenon in the brain) can change while the number and variety of components of the underlying physical machine (brain IPST) remain fixed⁶⁸. At the same time, OST and PST are causally linked and metastably unified [4]: Whenever any pattern of phenomenality is instantiated, there is a neurophysiological pattern of amplitude modulation⁶⁹ that corresponds to it.

The amplitude modulation pattern carried by a wave packet which is expressed in the quasi-stationary segment in a given local EEG signal does not *represent* the stimulus or perceived phenomenal features to other parts of the brain [26]. It just *presents* the relevant phenomenal qualia about the external objects or scenes for integration with wave packets (quasi-stationary EEG segments) from different cortical areas, to form a unified macroscopic (complex) phenomenal object, scene or thought as the culmination of an act of perception or imagination (see next Subsection). In this case, it is possible to consider each EEG segment as a single event in EEG-phenomenology. Within the duration of one such segment, the neuronal assembly that generates the amplitude modulation is in the steady quasi-stationary state [448], that corresponds to a particular operation⁷⁰ [25,222,451]. Each quasi-stationary EEG segment is separated from those preceding and following it by an abrupt transition during which the EEG amplitude changes significantly (Fig. 8), and thus imposes a discontinuity in local cortical dynamics [226,258]. The transition from one segment to another directly reflects the change in the activity of neuronal assemblies [193,434,475].

⁶⁷ Treuhub calls it the 3D retinoid [367].

⁶⁸ To illustrate this point we will use the citation from Sloman [472]: “For instance, by installing different software systems on the same machine we can change the operating system on a PC from Windows to Unix or Linux thereby changing a machine that supports only one user at a time to one on which different users can be logged in simultaneously running different virtual machines, even though no machine components have been changed. Of course, switching from one virtual machine to another involves different detailed physical processes when the machine runs, even if there is no re-wiring or replacement of physical components: the changes involve different sequences of operations in large numbers in the computer”. Compelling evidence for this comes from the findings reported by Ramachandran et al. [473,474] in which they show that despite dramatic changes in nonconscious brain anatomical topology (IPST in our interpretation), particular representations remain available to the consciousness and can still be experienced as sensations of pain or cold. We believe that this is so because the higher level spatial-temporal patterns (OMs in our interpretations) that comprise the OST level were still present in the brain.

⁶⁹ Empirical observations on the relation between the amplitude modulation of the EEG signal and the analytic phase of that signal indicated that a rapid change in phase tended to occur at a minimum in amplitude [26,193], thus indicating that phase modulation of the EEG signal is also involved in the construction of neurophysiological patterns which accompany phenomenal patterns. Additionally, it has been shown that frequency modulation (indexed by the synchronized abrupt changes of spatially distributed oscillations) is also important for described processes [242,243, 246].

⁷⁰ Such operations could be the representation of different attributes of objects, environmental scenes or mental images/thoughts as well as separate cognitive operations such as encoding, retrieving, and so on.

To uncover these segments of quasi-stationarity, which are ‘hidden’ in the complex nonstationary structure of local EEG signals, adaptive segmentation procedures⁷¹ should be used [226,258]. The aim of the segmentation is to divide the EEG signal into naturally existing quasi-stationary segments by estimating the intrinsic points of “gluing” – transitional periods⁷². These instants (the transient phenomena) observed within a short-time window, when EEG amplitude changes significantly, are identified as *rapid transition processes* (RTP) [30,226,258,436]. RTP is of minor length compared to the quasi-stationary segments, and therefore can be treated as a point or near-point [30] (Fig. 8). 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 a transition. Experimentally it was found, that amplitude transition in the RTP area is always extremely rapid – not less than twofold comparing with amplitude values in the close area before and immediately after RTP [444]. Thus, the RTPs (or jumps in EEG amplitude) are, in fact, the markers of boundaries between concatenated quasi-stationary segments (Fig. 8).

An adaptive segmentation approach allows estimation of several characteristics (attributes) of the obtained EEG segments [453]. These attributes reflect different aspects of neuronal assemblies’ functioning and thus permit the assessment of the mesolevel description of cortex interactions (interactions within transient neuronal assemblies) through large-scale EEG estimates (see [257] for experimental support and detailed discussion). In context of the present review, there are two important attributes that can be discussed: These are the *average amplitude* within EEG segments and the *average length* of EEG segments (Fig. 8). The former is measured in μV and, as generally agreed, indicates mostly the volume or size of neuronal assembly: Indeed, the more neurons recruited into an assembly through local synchronization of their activity, the higher the resulting amplitude of oscillations in the corresponding EEG channel [89,241]. The latter is measured in

⁷¹ One may think that the methodology of EEG segmentation, described here is identical or similar to Lehmann’s technique for the momentary whole-brain electric field segmentation [267]. It is worth to stress that this is not the case. Lehmann’s methodology is based on the calculation of the spatial localization of the vector of the maximal potential difference; therefore his technique searches (in contrast to the technique mentioned here) the sequences of stable whole-brain microstates. These microstates have a tendency to remain in a certain spatial configuration for a certain period of time, then change rapidly to a new configuration in which they stay stable again for a while. During a stable period, maps of whole-brain microstates increase and decrease in strength, as can be seen by the increased number of equipotential lines, but the topography remains unchanged. However, because this segmental methodology is based on momentary whole-brain electric field configurations, it does not provide information about the frequency domain. In such a case the relationship between microstates and frequency oscillations remains unclear. Another drawback of this methodology concerns the involvement of different cortical areas: Even though Lehmann’s spatial segmentation is a very important approach for studying the quasi-stationary structure of whole-brain activity, it does, however, lack time-dimensional information of each separate local cortical area. Yet another limitation in context of his method is that local EEG sites do not participate equally in the formation of the resulting dipole vector and this has not been justified from the viewpoint of indubitable neurobiological/functional equivalence of cortical areas. Lastly, there are only 4-5 classes of such whole-brain microstates; with this limited number of states it is very difficult to explain the extremely high number of cognitive and mental/conscious states.

⁷² In mathematical statistics this is known as the “change-point problem” [476].

milliseconds and indicates the functional life-span of neuronal assembly or the duration of operation produced by this assembly: Since the transient neuronal assembly functions during a particular time interval, this period is reflected in the EEG as a stabilized interval of quasi-stationary activity [258,434,449].

4.3. Synchronized quasi-stationary EEG segments, Operational Modules, and complex phenomenal objects

Although phenomenal consciousness is serial in the sense that we subjectively experience the succession of discrete and phenomenal objects, images or thoughts separated by rapid change, each phenomenal object, image or thought per se is unified and quite complex. This complexity requires the coordinated in time operations (equivalent of bioelectrical fields) of many neural assemblies (OST level), which are selectively emerged from the entire IPST of the brain [452]. Indeed, as we have discussed in the Section 3, to have an experience of any phenomenal object, for example the “apple”, several features of that object (shape, color, smell, texture, etc.) should be *spatially* and *temporally* integrated. In agreement with the above analysis, 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 produces complex brain operations [30]. As a result, metastable brain states emerge that accompany the realization of such brain complex operations, whereas each of them is instantiated by the volumetric spatial-temporal pattern in the electromagnetic field. We call these metastable spatially and temporally organized patterns in the electromagnetic field as *Operational Modules*⁷³ (OM) [30,451]. Based on the experimental findings we have further suggested that these OMs constitute a higher level of abstractness⁷⁴ [4,25,452]. For example, in an experiment aiming to study working memory, it has been shown that operations of functionally distant neuronal assemblies were preferentially synchronized, forming OMs, which were involved in different short-term (chronologically ordered) stages of memory processing such as encoding, retrieval, and retention,

⁷³ 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. As it has been reviewed in Section 2 the simultaneous existence of autonomous and integrated tendencies signifies the metastable principle of brain functioning [218-220,222].

⁷⁴ The abstractness of this level is reflected in the fact that the OMs are relatively independent from the neurophysiological process in the brain: Meaning that they are independent from the intrinsic brain anatomical topology that determines which single neuron of a given anatomical circuit produces which spike pattern of a given temporal signature (for similar argumentation, see [23,477,478]).

each of which required synchronization of many cognitive operations [289]. An analogous principle was found in the multisensory perception study [290] and other cognitive tasks [191].

The notion of operational space-time applies here. Intuitively, *Operational Space-Time* (OST) is the abstract (virtual) space and time which is “self-constructed” in the brain each time a particular OM emerges⁷⁵. Formally, the OST concept holds that for a particular complex operation, the *spatial* distribution of the locations of neuronal assemblies together with *synchronous* activity at repetitive instants of time (beginnings and ends of simple operations) comprises the OM (Fig. 9). 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 exact locations are relevant). Also, between the moments in time that particular locations of the neuronal assemblies synchronize, there can be smaller subset(s) of these locations synchronized between themselves or with other neural locations, though these do not relate to the same space-time of the same OM (although they may relate to some other OM). Therefore several OMs each with its own OST can coexist at the same time within the same volumetric electromagnetic field. The sketch of this general idea (based on real experimental data) is presented in Fig. 9.

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. 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 size (number of cortical locations involved) and life-span (temporal duration) [257,289,290,434,444,447]. We argue that at the phenomenological level, the lasting OM would be experienced as a “phenomenal present” of consciousness. This hypothesis remains to be proven experimentally, however some empirical evidence already exists. For example, 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 large OMs that cover a large part or indeed the entire cortex) to 30 sec (for small OMs). These accounts, including variations in duration, are consistent with known estimates of cognitive processes, and of highly dynamic “moments of experience” or “thoughts”, which may vary between ~100 milliseconds and several seconds depending on circumstances [405].

⁷⁵ Such understanding is very similar to Ukhtomsky’s [274] notion of “space-time interval”, which constitute the complex operation (or many integrated simple operations) with its own space-time needed to accomplish this operation. Therefore, each complex operation would have its own space-time interval, which is characteristic for it and depends on its current functional state [479]. For similar conceptualization see also van Leeuwen [213].

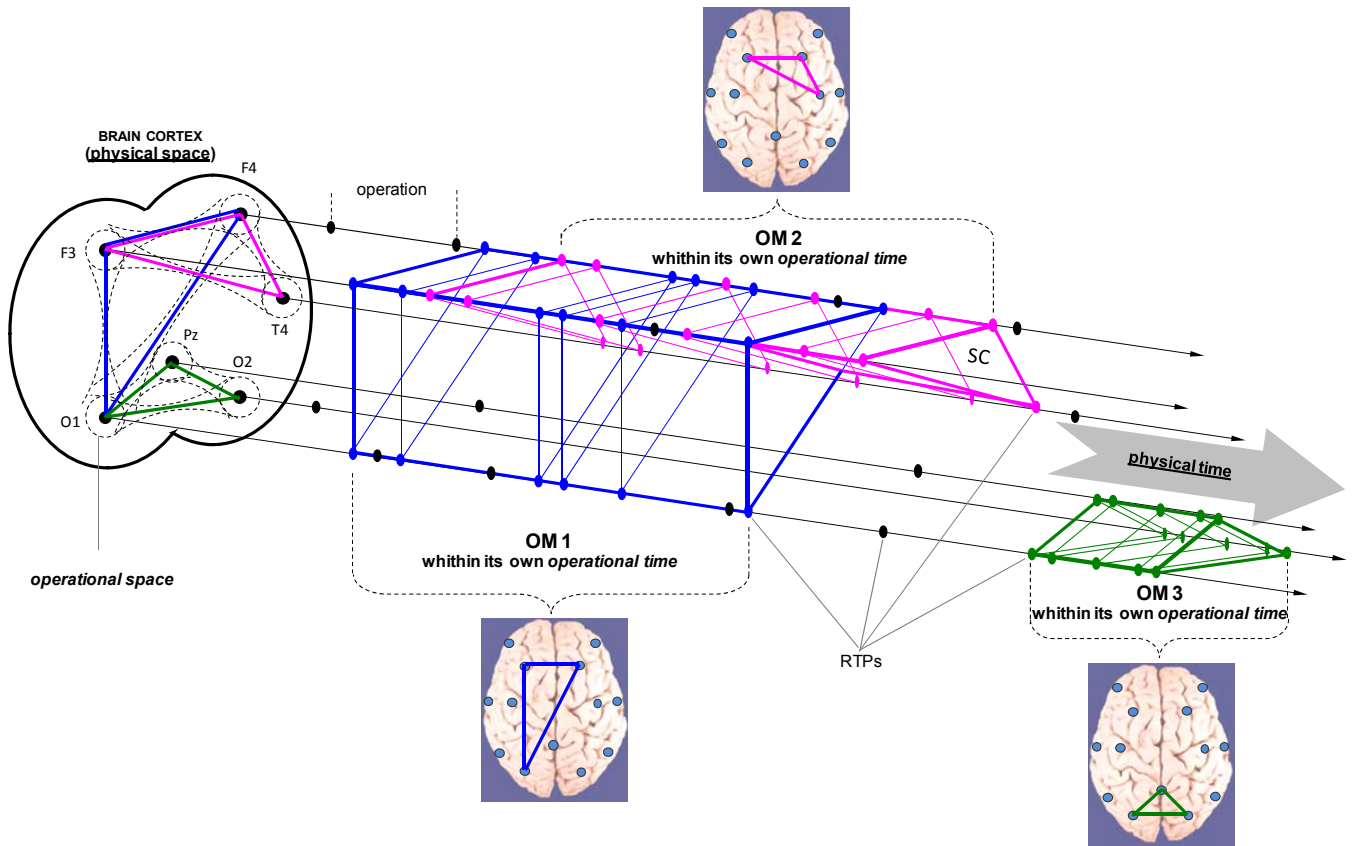


Figure 9. Schematic illustration of Operational Modules (OMs) and operational space-time (OST). As one can see, each OM exists in its own OST, which is “blind” to other possible time and space scales present simultaneously in the brain “system”. In the other words, all neural assemblies that do not contribute to a particular OM are temporarily and spatially “excluded” from the OST of that particular OM. Explanations are done in the text. RTP – rapid transitional processes (boundaries between quasi-stationary EEG segments); SC – momentary synchro-complexes (synchronization of RTPs between different, but particular, local EEGs at the particular time instants); F3 – the left frontal cortical area; F4 – the right frontal cortical area; O1 – the left occipital cortical area; O2 – the right occipital cortical area; T4 – the right temporal cortical area; Pz – the central parietal cortical area. As an example, it is shown that neural assemblies in these areas could synchronize their operations on three different (even though partially intertwined) spatial-temporal scales, thus forming three separate OMs each having its own operational space-time.

At the same time, it was shown that some OMs are surprisingly stable and persistent across all studied experimental conditions in all subjects [289,444]. We have demonstrated [Fingelkurts & Fingelkurts, forthcoming] that these highly stable OMs constitute the set of cortical areas that has been named as the “Default Mode Network” (DMN) [480]. Nowadays researchers tend to associate this DMN either with the stimulus-independent thought, mind-wandering and the internal “narrative” [481,482] or with the “autobiographical” self [481,483], “chronic” self-evaluation [484] being a “self”, or having self-consciousness [485-487]. Indeed, as we have discussed in Section 3, a subject that experiences phenomenal self-consciousness always feels directly present in the center

of an externalized multimodal perceptual reality [72,367]. This well-known (from the first-person-perspective) fact specifies that the sense of ‘being a self’ (probably in an implicit form) is always active even during realization of any cognitive or other tasks, independently of their complexity [367,488] and also in the dream state [489].

Our research has shown, that OMs (being by themselves the result of synchronized operations produced by distributed transitive 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 integrated experience [25,451,452]. 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 [25,451,452]. Therefore, OMs have a rich combinatorial complexity and the ability to reconfigure themselves rapidly, which is crucially important for the presentation of highly dynamic phenomenal experience (Section 3). 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 focused⁷⁶ conscious states [72,339]. Behavioral experiments where subjects are asked to concentrate their attention either on a complex scene or some part of it with parallel EEG registration (and OA analysis) could be used to verify this proposal.

However, OMs are not simply arbitrary volumetric spatial-temporal patterns from which the OST level of the brain is constructed, but instead have specific properties tailored so that the brain achieves optimal resource economy. The modular hierarchy divides up the population of operations performed by the brain into major operational modules in such a way that complex operations related to the same (spatially and temporally) phenomenal objects, scenes or actions are grouped together and the information exchange between separate modules is minimized as far as possible [210,490]. One general result of this process is that an OM of any complexity will tend to have much more information exchange internally (i.e. between its submodules – either simpler OMs or neuronal assemblies themselves) than with other OMs.

Haynes and Rees [491] argued that to date, it is not clear whether it is possible to independently detect several simultaneously occurring mental images/objects/thoughts. Detecting two or more such mental images simultaneously requires a specific method to reveal superposition states. A problem arises with such a decoding task because the spatial patterns indicating different mental images might (and probably do) spatially and temporally overlap. Methodological tools within the

⁷⁶ Focused conscious experience corresponds to a narrowing of the focus of awareness in relation to the complex scene or object. For example, when subject shifts his/her attention from observing the whole scene e.g. a forest or complex object as a whole, for instance a dog, to some part of it: A particular tree of the forest or head of the dog.

Operational Architectonics framework provide an opportunity to independently detect several simultaneously occurring mental states.

Considering the polyphonic character (mixture of different frequency oscillations, see Section 2) of the EEG field [8,149,154] and the hierarchical nature (different time-scales) of segmental descriptions of local EEG fields [30,226,258,436], 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 (for experimental support see [257,289,444] (see Fig. 9). 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 distributed stabilized activity (indexed as OMs)⁷⁷ within the same brain IPST.

We argue that this level of brain operational architectonics, the OST level, is functionally isomorphic with the organized patterns of qualities and with the full-fledged phenomenal objects of PST (see Section 3). The synchronization of operations produced by different neuronal assemblies, that located in different brain regions (i.e. operational synchrony), serve to bind spatially dispersed phenomenal features (bases of sensations) of a multimodal stimulus or objects into integrated and unified patterns of qualities and further into the phenomenal objects or complex scenes [25,451] with unique Gestalt and semantic windows⁷⁸ [72]. For experimental support, see [451]. From this perspective, the immediately needed cognitive or mental operations within a particular time-scale can be presented by immediately emerged specific OMs on the same time-scale and without the need to disassemble the persisting OMs which exist on different time-scales [4]. Experimental support for this proposal has been found in the cognitive [444] and memory [289] studies. This mechanism allows the brain to present multiple multimodal stimuli, objects, actions and/or tasks by distant (sometimes interleaved) OMs⁷⁹ without being functionally confused [495]. The same conclusion can be drawn from the study of Calhoun et al. [496].

⁷⁷ In this way, OMs lie, in some sense, between classical and connectionist architectures. They resemble connectionist networks [492] in many respects: They may serve as associative, content addressable memories, and they are distributed across many neural assemblies. Yet, the specific spatial-temporal patterns (OMs) per se are unitary, like symbols of classical logics [186].

⁷⁸ The same mechanism is supposed to be responsible for the grouping together of set of interrelated actions (for example, grasping a spoon, using it to scoop up some sugar, moving the spoon into position over a cup, and depositing the sugar), casting them as a single higher-level macro-action/macro-operation or skill ('add sugar'). Such new macro-operations are described as spatial-temporal abstractions because they abstract over spatially and temporally extended, and potentially variable, sequences of lower-level operations [493].

⁷⁹ In this context self-consciousness (indexed by persistent DMN OMs) has only a control function for behavior [494], while the concrete cognitive and mental operations are supported by specific and transient OMs that are responsible for the transient focus of conscious attention towards immediate external and/or internal stimuli and/or tasks/operations.

If all the brain could implement would be a complex enough but static OM, then such a brain would only experience the presence of one unified world frozen into an internal now [371]. Neither the complex texture of subjective time flow, nor true perspectivalness that goes along with a first-person point of view would exist. Therefore, what is needed is a dynamic succession of phenomenal moments that are integrated into the flow of subjective time. This will be discussed in the following Subsection in relation with the neurophysiological counterparts (succession of OMs).

4.3. The succession of OMs and the stream of consciousness

As it is evident from the first-person perspective, the actualization of full-fledged virtual, phenomenal objects, images or scenes (as well as higher-order thoughts) is realized on a ‘one-at-a-time’ basis, moving serially from one phenomenal pattern to another [72]. This process gives rise to a stream of consciousness [383]. According to James [383] the stream of phenomenological consciousness has inherent structure, which consists of stable nuclei (or thoughts) each of a certain (although not constant) duration and transitive fringes (or periods). A similar idea is expressed by Freeman [26]: “the stream of consciousness is cinematographic rather than continuous, with multiple frames in coalescing rivulets”⁸⁰. Experimental evidence suggests that the same is true for the cognitive and behavioral continuum, where each separate cognitive or behavioral act is expressed through the spatial-temporal integration of a certain number of operations, which are important and appropriate for the realization of these acts [385,493]. In all of the described domains (phenomenal, cognitive, and behavioral) the change from one stable period to another is embedded in the rapid transitional process [30]. The OA framework provides a natural explanation for how, in the words of Baars [502], “a serial, integrated and very limited stream of consciousness emerges from a nervous system that is mostly unconscious, distributed, parallel and of enormous capacity”.

According to OA, the metastable OMs at an OST level isolate, “freeze”, and “classify” at a PST level the ever changing and multiform stream of our conscious experiences⁸¹. Thus, 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 (see Fig. 10). As it has been shown experimentally, at the critical point of transition in mental state e.g. during changes of phases in memory or other cognitive task [289,444,446], the OM undergoes a profound reconfiguration which is expressed through the following process: A set of local

⁸⁰ See also other conceptualizations of the same idea [497-501].

⁸¹ Marchetti have discussed elsewhere [54] that this mechanism might be responsible for the production of the linguistic higher-order thoughts (see also recent work [503]).

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.

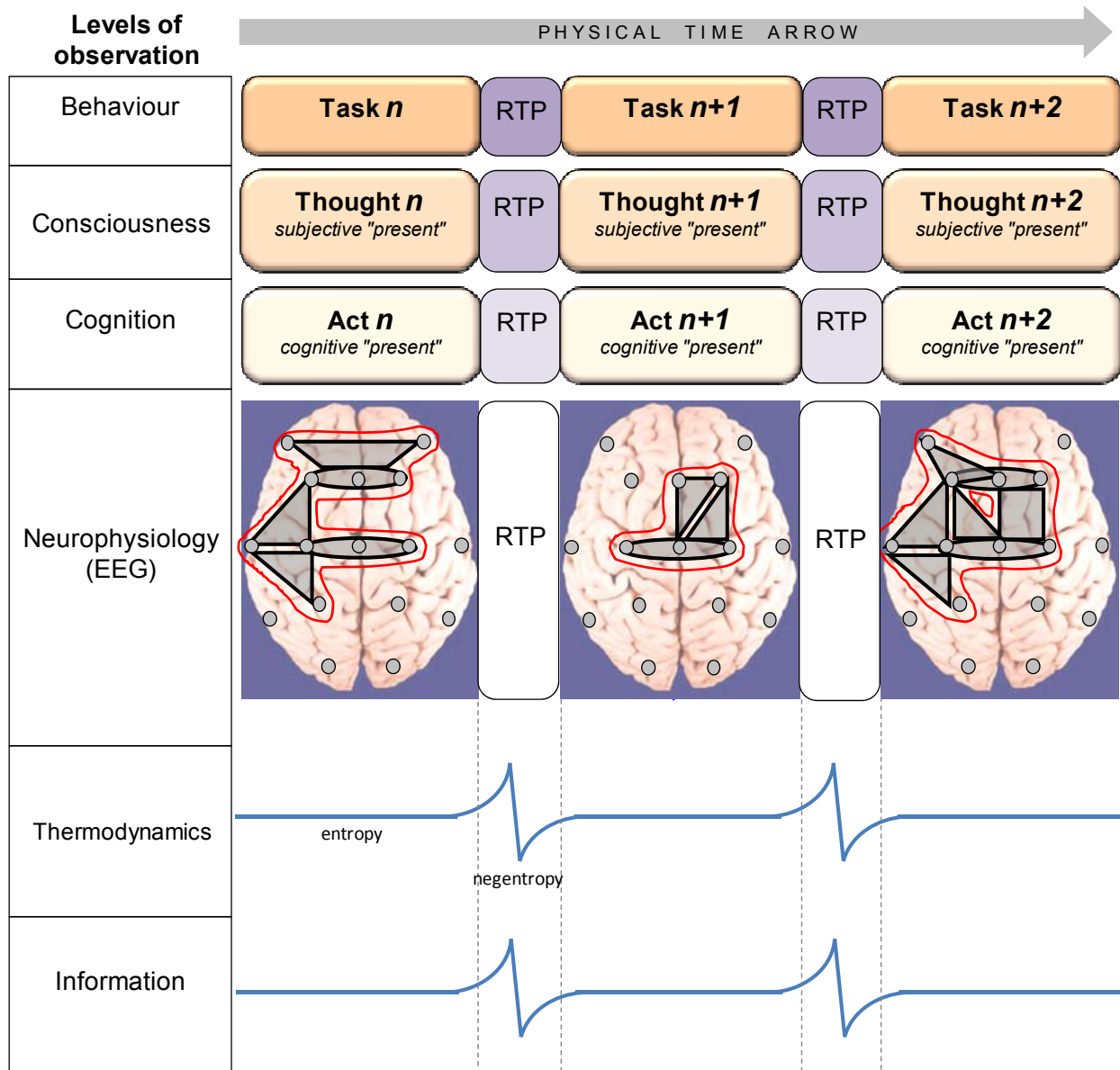


Figure 10. Schematic diagram depicting isomorphism between functional structures of cognition, phenomenological consciousness, behavior, and electromagnetic brain field, as well as thermodynamics and informational flow. As an example, the simplest case is shown, when cognitive, phenomenal and behavioral operations/acts coincide in time (in most cases these relations are more complex). Cognitive, phenomenological, 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; 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 assemblies are maximally decreased. Grey shapes illustrate individual OMs. Red line illustrates complex OMs. Changes from one complex OM to another are achieved through RTPs. For illustration purposes the OM experimental data are taken from the original study by Fingelkurts et al. [289].

Neurophysics [504] contends that within the transition there is also a brief period when the drastic and abrupt increase in degrees of freedom of neuronal assemblies is accompanied by a sudden increase in entropy and information⁸², followed by a quick reduction in the degrees of freedom of neuronal assemblies and rapid decrease in entropy and information [44,45] (see Fig 10). This second phase of transition period is indicative of the self-organization of a new representational state expressed in the form of a new OM within brain OST. Thus, in terms of Modern Critical Theory⁸³ [506,507], during a critical transition point the macroscopic manifestation (OM) is essentially based on a kind of abstraction from the original micro-level (neuronal assemblies with their local electromagnetic fields), with all but those micro-level features preserved (operations of neuronal assemblies) that now determine the novel macroscopic observable (OM) and presenting in fact a different biophysical state [38]. That is, the micro-level elements (neuronal assemblies) can now explore different structural relationships with each other. When these micro-elements arrive at a new configuration (OM), then the whole system (OST) exhibits different structure (for a general conceptualization see [49,508]).

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 OM are more stable. Kelso observed [509] that "stable thoughts, like stable gaits it seems, correspond to minimum energy configurations among participating neural ensembles". Indeed, research shows that oxygen utilization (Blood Oxygen Level) increases as the spatial-temporal pattern loses stability, suggesting that the demands on neural resources to sustain a given pattern stability also increase [510]. Therefore, each phenomenal object, scene or thought has

⁸² The parallel increase of information and entropy requires additional clarification. From the viewpoint of information theory [505], the information content of a series of states is highest if the entropy is maximal, which means that the predictability of the state of any part of the system from the states of the other parts is low, as well as the predictability of the state at any time from the state at other times. Thus, the information content of cortical activation is highest if neuronal assemblies are differentially and independently active and their overall activation shows no common regular time course (absence of any OM). However, if this differentiability goes further, a disruption of neuronal assemblies might take place, resulting in a general state which would be characterized by numerous singular neurons firing independently. Such a state would again have small informational content.

⁸³ Modern Critical Theory deals with abruptness of state transition's occurrence, triggered by certain control parameters assuming critical values [38].

its own typical spatial and temporal scales. Each stable phenomenal object within PST presented as a stable OM within OST is experienced as an island of presence (duration) in the continuous flow of physical time in EPST (see Fig. 10).

The other important question concerns the transition period: What causes phenomenal objects, scenes or thoughts to switch? Considerable experimental evidence demonstrates that switching in both mind phenomenal and brain spatial-temporal patterns is a *self-organized process* that takes the form of an abrupt nonequilibrium transition [43,50,93,289,290,417,444,446,450,453,511-514]. This mechanism has been proposed to work in spontaneous thinking or “mind wondering”, when there is narrative of thoughts and images, which persists without disruption. On the contrary, in the process of “forceful” or deterministic thinking, the laws of logic and language take a major role (however, the discussion of this aspect is beyond the scope of present review; see [503]).

Thus, provided OA explanation of the succession of phenomenal images or thoughts helps understanding of how the subjective time flow is (cognitively) (re)constructed beyond the phenomenal horizons of “presence”. Time flow is not actually experienced or ‘perceived’, it is the product of cognitive higher-order processes operating on the OMs. Such higher-order processes are also expressed in the form of OM (but in that case of higher complexity), which not only reads off superceeded lower-level OMs, but also execute memory consolidation and retrieval operations [289]. Given such a mechanism, the variety of subjectively experienced speed of time could be also explained. In terms of the OMs description, when the OMs’ duration gets shorter, there are many more OMs managing to sequence each other within a time unit. We suggest that this overflow of OMs would be commonly experienced as an acceleration of the subjective time and, respectively, deceleration of the outer physical time. If the duration of OMs were to extend, then the opposite subjective experience would emerge – deceleration of subjective time and acceleration of outer time.

5. Concluding remarks, implications, and predictions

The gap⁸⁴ in knowledge between the brain and the mind can only be bridged with an understanding of how brain operational-space-time and mind phenomenal-space-time are unified within the same metastable continuum [4]. In accordance with this perspective, the approach to be followed is based on the central tenet that there exists a functional isomorphism between brain

⁸⁴ In the words of Revonsuo [72] this “gap is created by missing levels of description in our current understanding of the brain”.

operational- and mind phenomenal-space-time structures; and this allows researchers to study brain-mind relations within the same methodological framework.

The intuitive sense of fundamental correspondence among the brain's physical structures of neurocognitive networks, the dynamic patterning of their active states, their operations and the subjective counterparts can be traced back to Fechner [515], Mach [516], Müller [717]; Vygotsky [518], Luria [519], Ukhtomsky [274], and Anokhin [520] and up to modern neuroscientists [6,8,9,23,26,73,78,91,213,233,265,309,469,521-528].

In this review paper we have tried to draw a coherent picture of brain-mind functioning based on general concepts of space and time. We have tried to substantiate our general approach by a rather explicit framework of Operational Architectonics according to which the mind phenomenological architecture and brain operational architectonics represent complementary aspects of the same unified metastable continuum [4]. In this Section we want to draw several general conclusions.

We have argued here that the metastability mode of brain-mind functioning [219,223,509] introduces a hierarchical coupling [6,26] between the brain and mind while simultaneously allowing them to retain their individuality (for a conceptual discussion see [4]). When examined from this perspective, mind, cognition, and behavior, as well as brain activity, are all seen as dynamic processes that rapidly evolve through a series of informationally consistent, spatially and temporally organized coordination states (Fig. 10). In each moment of time, these states (of varying complexity) are defined by the selective coordination of local cortical neuronal assemblies that are interacting by virtue of synchrony of their local electromagnetic fields which are equivalent to functional operations (OST) within the large-scale anatomical structure of the cortex (IPST).

Based on the analysis provided in this review we may conclude that 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 (Fig. 11). The operational level *ties* these two (neurophysiological and subjective) domains ontologically together through the shared notion of *operation* [4]. In this sense if, for example, the physical body moves in physical space and time, the body phenomenal image moves in phenomenal space-time⁸⁵. The causal relations mentioned here are of the Humean type: Whenever a certain event A (spatial-temporal pattern) occurs in the brain

⁸⁵ However there are exceptions: During dreaming there is a total paralysis of voluntary muscles (with exception of those responsible for breathing and eye movements); therefore, the dream phenomenal image of self can move without actual physical movement in the physical world (see however, footnote 87).

OST, an appropriate kind of event A' that corresponds to A occurs in the relevant spatial-temporal part (PST) of the phenomenal consciousness⁸⁶.

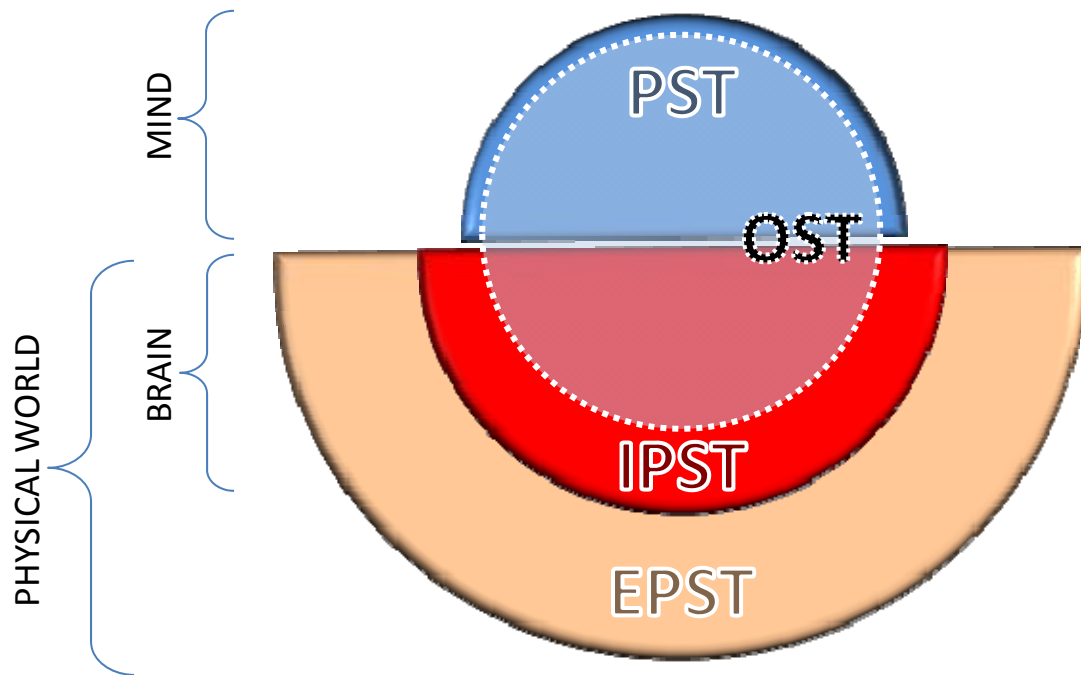


Figure 11. Relations between different levels of the brain-mind organization. EPST indicates the external physical world space-time (light brown color); IPST indicates the internal physical space-time of the brain (red color); OST indicates the operational space-time of the brain (indicated by white puncture line); PST indicates the phenomenal space-time of consciousness (blue color). In this model the OST level represents the constitutive mechanism of phenomenal consciousness and ties the phenomenal (subjective) and neurophysiological (physical) levels together.

Furthermore, based on the provided review we conclude that the whole operational level of brain organization, where all OST phenomena reside and interrelate, forms a higher level of brain organization where all conscious phenomena exist. That is to say that OST level does not “emit” consciousness in any mysterious way, but rather it simply constitutes it (Fig. 11).

However, this unified metastable continuum could not be independent (in a healthy organism) of outside events of the physical world (EPST). Indeed, it would be rather inconvenient to fall asleep while crossing the road with hectic automobile traffic or try to go through a wall because it is not present subjectively at the phenomenal level⁸⁷. Thus, the brain needs to contain (or construct) a

⁸⁶ For similar argumentation and further discussion of this topic see Smythies [333].

⁸⁷ However, such situations can exist in some pathological conditions. For example, REM sleep behavior disorder (RBD) refers to a pathological condition in which the usual condition of muscular atonia is removed for the dreaming;

continuum of dynamic spatial-temporal patterns from a multisensory stream of neural events caused by the spatial-temporal patterns of the outside physical world. The IPST of the brain is responsible for such “processing”, that is, the reordering and recombination of signals from the outside physical world⁸⁸ (EPST). IPST level transforms external spatial-temporal relations of the EPST into highly structured and dynamic spatial-temporal relations of local extracellular electric fields of neuronal assemblies, where volumetric, operational spatial-temporal patterns (OST level) originate (Fig. 11). These operational patterns (OMs) directly present phenomenal spatial-temporal patterns and, thus, serve as a transparent surrogate of an even higher level of abstractness — PST. The PST, in turn, also serves as a transparent surrogate of the EPST of the world. This perspective, therefore, suggests how brain-mind operational architectonics reflects the organization of the physical world, with which brains (including their subjective virtual worlds) interact⁸⁹.

It will take some time to obtain direct experimental evidence for this proposal (see Subsection 5.2 below); however, with OA framework discussed in this Section (and Section 4), the brain-mind interaction does no longer seem so mysterious. The neurophysiological reconceptualization of consciousness we proposed here is not a reduction of subjective phenomenology to something else. It is an attempt to provide a low-level (in comparison with higher phenomenal level) neurophysiological explanatory mechanism of consciousness that takes into account what phenomenal consciousness feels like from the first-person perspective. It also depicts the relations between consciousness, brain and external physical world in a scientifically plausible way.

5.1. Methodological aspects and implications

and complex, often distractive behaviors are manifested, because the subjects act according to their dream and do not noticed real physical environment [529,530]. These cases clearly indicate that complex behaviors of such subjects are guided and motivated by the phenomenal contents of consciousness only. Dreamers interact with and adapt to the “simulated” world in the dreaming brain, in which they are totally immersed. Needless to say that during an RBD episode, such a radical mismatch between the real physical environment and the phenomenal world causes highly maladaptive physical actions of the dreamer, which often result in injury to the patient and his/her close mates. Analogous problems are manifested in schizophrenic patients during complex hallucinations [531,532].

⁸⁸ This allows for the phenomenal level be in online resonance with external objects present out there in external physical space. The internal consistency and complexity of the phenomenal world can only be achieved by “virtue of systematic causal relations to [...] the external physical world that science postulates to lie out there” [72; p. 123].

⁸⁹ This view is similar to the philosophical analysis of Russell [533] who stated that external physical events are known “so far as their space-time structure is concerned, for this must be similar to the space-structure of their effects upon percipients” (p. 229) and to Dainton’s view [534] who suggests that the neurophysiological activity of the brain is somehow using the physical space-time which it occupies from moment to moment to realize phenomenal qualities with inherent spatiality and temporality.

Currently there are several theoretical attempts to integrate brain and mind within the same framework [14,23,26,309,380,535-538]. However, practically all of them do not take phenomenal consciousness of mind seriously and at best try to explain it through its neural correlates [539-541] despite the fact that ‘correlation’ is too weak a relation to be definitive in any explanation [72]. Another serious drawback of such theories is the fact that they postulate many entities which cannot be readily measured in practice, and their experimental exploration stands as an important challenge [542]. Furthermore, even when phenomenology is considered, such theories either do not take the dynamical and compositional nature of the phenomenal world seriously or disagree about the relevant for the consciousness level of brain organization.

The OA framework is quite different in this respect⁹⁰. According to OA theory, if the phenomenal mind is at the biological level of brain organization then it follows that the spatial-temporal structure of some higher level of its organization (OST level) corresponds to (or is functionally isomorphic with) the structure of the phenomenal (PST) level itself [4]. According to this review, the presented approach is physiologically and theoretically plausible and leads to several interesting implications for linguistic semantics, self-organized distributed computing algorithms, artificial machine consciousness, and diagnosis of dynamic brain diseases. Detailed description of these implications is provided in [4]; however, here we would like to emphasize three important aspects, which have not been observed in that work.

First: One major and long-lasting question in cognitive neuroscience concerns the problem of parallel or serial processing, especially concerning memory scanning and item recognition [543], or serial models of word processing. Although behavioral research has led to the suggestion that memory scanning is serial and exhaustive [544], parallel search models have been proposed also [545]. Within the OA framework described here the dichotomy between parallel and serial neural processing (as well as local *vs* global processing) becomes irrelevant, since both ends of the dichotomy can be embodied and observed in the moment-by-moment states (OMs) of large-scale network of neural assemblies. Indeed, as it follows from experimental studies [289,444], parallel processing is performed by simultaneously active individual and separate neuronal assemblies, whereas serial processing emerges as a result of formation of OMs and abrupt shifts between them [30,222,451]. For example, it has been experimentally shown that operations may couple in time as a triplet (or quadruplet, and so on) of cortical areas A, B and C, but not as an individual pair in areas B and C (without simultaneous operations in A) [444]. This process has been suggested as a kind of

⁹⁰ Even though OA framework has some similarities with other theoretical conceptualizations, it is quite distant from them in its core principles (for detailed analysis, see the last Section in [258]). Most importantly, and in contrast to many other theoretical frameworks, in the context of OA framework, there is a range of methodological tools which enable in practice to measure, estimate, model, and describe the postulated entities of the theory [258].

fast parallel information processing, because several operational flows in different cortical areas are executed simultaneously [154,546]. Another scenario is that when the RTP in EEG channel A often precedes an RTP in EEG channel B with relatively constant time delay; this can be considered as an evidence for a serial processing: The operational ‘switches’ reflected in A probably cause those in B. Thus, OM may combine and unite two different strategies of information processing that could allow the multiplexing of different memories within the same OM, and thus could enhance memory capacity. This interpretation is consistent with Townsend’s [547] models of rapid information processing involving parallel processing. It is also in line with the well-established viewpoint that encoding and retrieval of information in neuronal tissue requires some sort of binding mechanism that allows the expression of specific relationships between different brain areas (for the review, see [548]).

Second: Another important question concerns the understanding of pathological brain-mind conditions, which may be regarded as disorders of neural coordination [78]. The OA findings [549] suggest a loss of dynamical (but metastable) balance between local, specialized neuronal assemblies’ functions and global integrative processes during different (schizophrenia, major depression, opioid abuse, withdrawal) pathological conditions. It was shown experimentally that all of the studied pathological conditions could not reach a proper (for the healthy brain and mind) resting state where individual neuronal assemblies (located in different brain areas), besides expressing their own functioning, are also heavily involved in a collective activity to support normal subjective experiences [549]. These findings lead to the conclusion that such optimal resting state in the brain depends upon a delicate metastable balance between local specialized processes and global integration. Excess or lack of either component would be a deviation of the optimal situation (see also [2,123,550]). At the same time, our data pointed to the fact that not all characteristics of neuronal assemblies’ dynamics and their functional interrelations during a particular pathological condition are incompatible with dynamics of normal brain functioning. In this context a particular pathological condition may be conceptualized as an adapted state – a new metastable regimen of brain-mind functioning around altered homeostatic levels [549].

Third: In our recent work [551] we have discussed a conceptual framework, which may offer an alternative path in engineers’ attempts to create a “machine” (robot) consciousness. According to OA framework, the phenomenological architecture of consciousness and the brain’s operational architectonics correspond with one another; and they may also share ontological identity. If this holds true, then we can make another claim that by reproducing one architecture we can observe the self-emergence of the other. Then, the problem of producing man-made “machine” consciousness is the problem of duplicating the whole level of operational architecture (with its inherent governing

laws and mechanisms) found in the electromagnetic brain field, which directly constitutes the phenomenal level of brain organization. This approach is radically different from those that try to model input-output descriptions of functions that consciousness normally plays out. Indeed, the fact that any system fulfils the input-output function(s) of consciousness does not logically entail that the system should enjoy any subjective experience per se [72]. A true conscious system (including an artificial one) is a system which the “brain’s” operational architectonics is capable of generating and supporting the phenomenal level of organization. This distinction is a well-known dichotomy between the Weak Artificial Consciousness (WAC) and Strong Artificial Consciousness (SAC) [552], where the WAC deals with design and construction of machines that simulate consciousness or cognitive processes usually correlated with it, while the SAC aims to design a true (genuinely) conscious machine [4].

In contrast to many theoretical approaches, the OA framework offers a range of methodological tools which enable to measure the postulated entities of the theory in practice [258]. For example, the specific tools of EEG analysis [30,258] are especially suited for the analysis 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 multiscale architecture. 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, *we can now explore the phenomenal architecture of mind (PST) by measuring the brain operational space-time (OST) architectonics* (see the following Subsection for detail).

Furthermore, the OA framework deviates dramatically from the frequent traditional approaches taken in neurocognitive science. Following Revonsuo [72] we propose that it is both possible and instructive to consider phenomenological structure of consciousness in non-representational terms. Clearly, this structure appears sufficiently stable (quasi-stable) in the short term (experienced ‘now’) and this property allows it to be described in symbolic terms. However, if we wish to tackle the issue of emergent properties that lie at the core of the phenomenology, the symbolic description will benefit from an explicitly non-symbolic account which can be derived from nonlinear dynamics. Taking a step in this direction means reconciling the symbolic description as follows: The dynamic spatial-temporal brain organization (IPST) does not represent information to any mental faculty but, rather, directly presents it within the operational structure (OST) which in general case refers to the outside physical world.

5.2. Predictions for future research

Relating the OA framework to direct evidence about phenomenal consciousness is a subject of ongoing and future research. This research will conform, disprove, or suggest modifications to the specific hypothesis considered in Section 4. In this Subsection we will mention several predictions that follow from the OA framework and are directly related to the theme of this review paper: Spatial and temporal organization in brain and mind. Many more important predictions can be made using the OA framework, but since they are beyond the scope of this review they will not be considered here.

Experimental investigation of phenomenal experiences is not an easy task because in everyday human life these experiences always “melt” with behavioral and/or cognitive processes and acts, which possess their own EEG correlates. This is why cognitive neuroscience developed specific methodological tools and experimental models to use in consciousness studies; these are commonly accepted in the field. The aim is to contrast phenomenal experience and to obtain conscious phenomena in a “pure” form. Several experimental models are used for the purpose: psychopathology, dreaming, illusions and hallucinations, hypnosis, and anesthesia. Some of these models will be used in this Subsection.

According to the OA framework, the shorter the duration of operations of neuronal assemblies (indexed by the EEG quasi-stationary segments), the finer the subjective perceptive temporal grain, resulting in a quicker reaction time. This prediction is confirmed in our earlier study [290]. It has been shown that faster reaction times of subjects are directly correlated with shorter duration of EEG quasi-stationary segments. Future research should demonstrate how this dependence is related to the formation of simple and complex OMs.

OA suggests that complexity of conscious experiences is related to the complexity in operational organization of the electromagnetic field. Therefore the prediction is that the subjective experience of infants should be completely different from that of adults. However, there are two opposite points of view in this respect. According to the first, infants would have subjective experience expressed as a collection of completely different and totally unrelated phenomenal patterns and/or objects [383]. It is supposed that their subjective experience does not yet possess a relational structure and therefore infants do not have full-fledged consciousness. According to the opposing point of view, the original state of subjective experience in infants is expressed as

undifferentiated and totally unified⁹¹; this could account for the limited abilities of the infant's mind [73]. Hence, in both cases a full-fledged (adult) conscious experience is typically absent. The OA framework predicts that in the first case operational architectonics should favor independent processing of neuronal assemblies, while in the second case operations of neuronal assemblies should be completely synchronized. In this way the OA methodology could help to resolve this problem.

A similar problem exists in anesthesia: Total unity/synchronization or total disunity/segregation of the operations of brain neuronal assemblies would instantiate the loss of consciousness. Future research with OA methodology will provide the necessary experimental evidence to favor one of the mechanisms of phenomenal consciousness loss under the influence of anesthetics.

According to the OA framework, the duration of the neuronal assemblies' operations (indexed by EEG quasi-stationary segments) and complexity (as well as diversity) of OMs should be consistent with the duration of phenomenal presence. Therefore, we predict that the life-span/diversity of neuronal counterparts (indexed as EEG quasi-stationary segments and OMs) of the subjective experience should be longer/lower when subjects experience "long-standing" thoughts, and shorter/higher when they experience "short thoughts". Even though some behavioral experiments could be constructed to test this prediction, the best experimental model specific to this prediction would be patients with schizophrenia, who have particular symptoms ("standing thought" or "fast stream of thoughts") of a diagnostic importance. In such patients, the temporal conscious phenomena are manifested in their clearest form and will not be easily confused with any other phenomena or contaminated by other cognitive processes.

The variation of this research would be to test whether the patient's subjective experience of the speed of thought could be modified pharmacologically to shorten or prolong the subjectively perceived duration of the conscious thought. It is well known that a number of pharmacological agents create subjective time distortions when administered. For example, nootropic drugs/opioids can be used as pharmacological agents, which shorten/prolong the subjectively perceived duration of the thought. At least for opioids it has been shown that these drugs do indeed increase the duration of the life-span of neuronal assemblies (indexed by EEG quasi-stationary segments) and limit the synchronization between their operations, thus reducing the possible number of OMs [458].

⁹¹ This situation is, for example, characteristic for epileptic patients, whose seizures are accompanied by a full loss of consciousness [553].

Another important model, where subjective experience is presented in a contrasted form (which could be easily manipulated), is hypnosis. In a pure⁹² hypnotic state the subject experiences an altered background state of consciousness different from the normal baseline state of consciousness [555]. This subjective state is characterized by some sort of “emptiness” or “absorption” brought about by dissociations in the cognitive system, such that separate cognitive modules and subsystems may be temporarily incapable of normal communication with each other [556,557]. Additionally, it has been shown that the sensation of time passing is stretched during hypnosis, because internal events are subjectively slowed [558,559]. Adhering to the tenets of OA framework, these subjective experiences should be reflected in the operational architectonics of the electromagnetic brain field. In a pilot study [456] it was indeed shown that the functional life span of all neuronal assemblies (indexed by the EEG quasi-stationary segments) was significantly longer during hypnosis when compared with the normal, baseline, conscious condition. It was further found that the number and strength of synchronized operations among different neuronal assemblies were significantly lower during hypnosis than during the baseline, thus limiting the possibility for any OMs to emerge. As a result they were absent [456]. Since OMs represent the formation of integrated conscious experiences, their absence may explain such unusual subjective experiences during pure hypnosis as amnesia, timelessness, detachment from the self, a “willingness” to accept distortions of logic or reality, and the lack of initiative or willful movement [560].

The momentary phenomenal consciousness leaves a trace in the working memory; and this trace can be recovered under certain experimental settings [561]. The working memory refers to a brief “on-line” storage of information, which is characterized by the following properties [562]: Its contents are rich, it is persistent – meaning that there is a phenomenal trace of the stimulus that has already physically disappeared, and its contents decay rapidly. The OA framework predicts that concrete combinations (indexed by OMs) of functionally coupled operations of neuronal assemblies would indicate selective channeling of information to different phenomenal contents, concurrently and selectively presented by different neural assemblies. Our findings [289] pointed that different stages of memory processing (encoding, retention, and retrieval) involved different sets of OMs of varying complexity. This was expressed through a gradual increase in the complexity of operational synchrony process, together with a growth of mental loading. Thus, the principle finding was the existence of systematic specific OMs, which changed significantly through the memory task [289]. These data suggest that the contents of momentary phenomenal consciousness emerged during encoding (reflected in small amount of simple OMs), during retention they persist as phenomenal

⁹² Pure (or neutral) hypnosis refers to a state where hypnosis is brought about by hypnotic induction alone, without any additional tasks or suggestions given to the subjects [554].

traces and were matched to existing phenomenal classes (this processes were reflected in a larger set of more complex OMs), and during retrieval period those contents were brought into reflective consciousness⁹³ (large set of new complex OMs were present).

The main point of the OA framework is that operational synchrony may represent a binding mechanism [25, 30, 222,] that is responsible for the integrated subjective experience. Thus, one predicted consequence would be a disruption in the OA (measured by the diversity and complexity of OMs) in patients with particular lesions or schizophrenia as compared to healthy subjects. It is well known that schizophrenics seem to lose the ability to have an integrated, interrelated phenomenal experience of their world and ‘self’ altogether [563]. This prediction was indeed supported by the experimental results of a pilot OA study [460]. Therefore, we reasoned that disruption of the OA of electromagnetic brain field (expressed as a “disorder of the metastable balance” in terms of [564]) is a contributing mechanism in the disorganization syndrome (a psychopathological dimension in schizophrenia [565]) of schizophrenic patients. Other patients with disorganization syndrome should also be studied for the same purpose to understand the generality of this mechanism.

Another prediction of the OA framework in relation to the integrated subjective experience is the supposition that conscious multisensory integration should be reflected in a particular complex OA organization of the electromagnetic brain field and that this architectonic should differ significantly in cases where such conscious multisensory integration failed. Experimental results of the odd-ball paradigm (using a robust illusion known as the McGurk effect⁹⁴ [566]) fully support these predictions [290]. In all subjects who subjectively experience multisensory integration from auditory and visual modalities (have the McGurk illusion) this phenomenal integration was achieved through the process of operational synchrony among modality-specific and non-specific neuronal assemblies distributed along the cortex [290]. On the contrary, subjects, who did not display the McGurk illusion, meaning that they did not subjectively experience multisensory integration, demonstrated significant uncoupling between functional operations produced by different modality-specific neuronal assemblies.

The OA framework also makes other predictions in relation to the multisensory integration of subjective experience: (a) incongruent multisensory stimuli (when subjects are *aware* of different sensory streams) should be instantiated by longer operations of neuronal assemblies due to

⁹³ Reflective consciousness operates on the contents of phenomenal consciousness [72].

⁹⁴ The McGurk illusion [566] refers to the effect when normal listeners report hearing audio-visual 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/). A vast majority of people experiences the McGurk illusion.

conflicting streams of conscious events when compared with the congruent multisensory stimuli (subjects are *unaware* of different sensory streams); (b) the shorter operations of neuronal assemblies should accompany multisensory integrated percepts, which are subjectively recognized faster than unimodal percepts. Results from the multisensory perception study [290] are in line with these predictions. Neuronal assemblies' operations (indexed as MEG quasi-stationary segments) tended to be of a longer duration in response to the presentation of incongruent audio-visual stimuli compared to congruent audio-visual stimuli response. Also for audio-visual stimuli (unified percepts) the duration of neuronal assemblies' operations (indexed by MEG quasi-stationary segments) was significantly shorter than for unimodal stimuli, independent of modality. Future research should reveal how these findings about discrete operations of neuronal assemblies are related to OMs of different complexity.

The OA framework suggests functional isomorphism between the dynamic phenomenological structure of consciousness and dynamic structure of the electromagnetic brain field [4,30,222]. Thus, another set of experiments should concentrate on directly studying this isomorphism. Such experiments would contrast the same content of consciousness caused by two different mechanisms: First, for example, by imagination (e.g. the subjective experience of seeing a particular object) and second, by an actual visual stimulus, showing the actual object during wakefulness. Multichannel EEG should be registered during these two conditions with subsequent calculation of OMs and estimation of EEG quasi-stationary segments duration. If the functional isomorphism principle is correct, then the conscious contents imposed by imagining and seeing the same object should be expressed by the same number, set, and duration of OMs. Also, experiments in which perceptual conscious experience changes without any change in the external physical stimuli (multistable illusions or illusory contours [93,567], 3D-object generating autostereograms [568], the Mooney face figures [569], or the pop-out effect [570]) can be used for the same purpose.

Dreaming is a special case of realization of phenomenal world in the brain in its pure form, when it is almost totally isolated from the external physical world and the rest of the body (see Section 3 for references). Dreams can appear in REM as well as in the nonREM sleep [356,571]. However, the nature of dreams in REM and nonREM sleep is different: For example, during REM the dreams are complex, organized, temporally evolving, multimodal, and often bizarre [572], while in nonREM the dreams are characterized by simple, static or isolated image(s) or thought(s) usually of one modality [573]. The OA prediction is that nonREM dreams should be accompanied by short-lived small neuronal assemblies and long-lived large neuronal assemblies, and by the significant increase of operational synchrony (poor set of OMs) among different neuronal assemblies in order to subjectively present static images or thoughts. On the contrary REM dreams should be supported

by the short life of all neuronal assemblies and highly dynamic and selected operational synchrony leading to a diverse set of transient OMs. In a pilot nonREM sleep study⁹⁵ (data not published) we found that nonREM dreams were indeed accompanied by the short-lived small neuronal assemblies, long-lived large neuronal assemblies, and by the significant increase of operational synchrony in the OA organization in the brain. Future research should be organized to confirm (or disprove) this finding in a larger representative sample study and to establish the OA data for REM sleep dreams.

The OA framework has an important practical aspect related to the conscious phenomenal state(s). In the future its methodological tools can allow the establishment of objective and reliable neurophysiological markers that could tell researchers and medical professionals exactly when conscious phenomenal patterns occur and when they are absent⁹⁶. This would be of crucial importance for anesthesiology interventions and for the reliable distinguishing between vegetative patients, who supposed to be lacking of the phenomenal level altogether, and patients with minimal conscious state, who are otherwise indistinguishable from vegetative patients. Also in a number of other neurological pathologies such an objective marker for phenomenal presence of consciousness in the brain would be beneficial.

As it follows from the brief review of this Subsection most of the predictions lead to experiments yielding results that prove these predictions correct; the rest need to be validated by the future research. Even though the OA framework per se is still incomplete and there are several predictions which require experimental validation, we argue that there is a sound perspective on further developing such neurobiological approach to account for the problem of phenomenal consciousness within a unified theoretical framework of brain-mind functioning.

We would like to conclude our review essay with the words of Barbour [574]: “Nothing in the material world gives us any clue as to how parts of it (our brains) become conscious. However, there is increasing evidence that certain mental states and activities are correlated with certain physical states in different specific regions of the brain. This makes it natural to assume, as was done long ago, that there is psychophysical parallelism: conscious states somehow reflect physical states in the brain. Put in its crudest form, a brain scientist who knew the state of our brain would know our conscious state at that instant. The brain state allows us to reconstruct the conscious state, just as musical notes on paper can be transformed by an orchestra into music we can hear.”

⁹⁵ EEGs during nonREM sleep was collected by Valdas Noreika.

⁹⁶ Currently there are several attempts to create such objective markers. However, all of them either “work” only in isolated cases, or only weakly correlated with the levels of consciousness.

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