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Consciousness as a Phenomenon in the Operational Architectonics of Brain Organization: Criticality and Self-Organization Considerations

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Abstract: In this paper we aim to show that phenomenal consciousness is realized by a particular level of brain operational organization and that understanding human consciousness requires a description of the laws of the immediately underlying neural collective phenomena, the nested hierarchy of electromagnetic fields of brain activity – operational architectonics. We argue that the subjective mental reality and the objective neurobiological reality, although seemingly worlds apart, are intimately connected along a unified metastable continuum and are both guided by the universal laws of the physical world such as criticality, self-organisation and emergence.

Key words: phenomenal consciousness, brain organization, nested hierarchy, electroencephalogram (EEG), criticality, self-organisation, emergence, fractal dynamics, neuronal avalanches.

"all human behaviors, including thoughts, undirected or goal oriented actions, or simply any state of mind, are the outcome of a dynamical system -the brain- at or near a critical state."

Chialvo [1]

"Understanding the brain is among the most challenging problems to which a physicist can be attracted. As a system with an astronomical number of elements, each one known to have plenty of nonlinearities, the brain exhibits collective dynamics that in many aspects resemble some of the classic problems well studied in statistical physics."

Chialvo [2]

"What we require now are approaches that can unite basic neurobiology and behavioral sciences into a single operational network."

Purpura [3]

1. Introduction

Given human evolutionary sophistication, our brain, that makes us the feeling, talking, knowing, society-building, socially complex species, gave us at some point in the history of the physical world an unprecedented gift – *consciousness* – the entity that none can still easily define, but nearly all accept that it exists [4,5]. This entity turns a mammal into a *human being* capable of self- and environmental awareness. From this point in time, the faded pieces of the external physical world are transformed as images into nonmaterial clusters of reality, and these clusters form what is called mental or "*virtual*"[1] reality [8]. Having unlimited degrees of freedom, infinite combinatorial power and being momentarily accessed for self-presentation, these mental images become subjects of the remarkable theater of mental psychological reality [9]. Thus, in humans and through humans nature becomes *aware of itself*. Indeed, without us, conscious human subjects, the physical world has absolutely no way of knowing of its own existence, neither is there reality of lived subjective experience or sensation [7].

[1] Here the term "virtuality" is used in the same way as in the computer engineered "virtual reality" [6]. 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 subjective world which could not be found in the brain's anatomy. Phenomenal world is thus "virtual" for precisely the same reason [7]: 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.

We have argued previously [10] that phenomenal consciousness refers to a higher level of organization in the brain 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). In this definition *phenomenal* means *subjective*: someone possesses phenomenal consciousness if there is any type of subjective experiences that is currently present for him/her. This notion follows a biological realism approach to consciousness proposed by Revonsuo [7]; according to which subjective consciousness is a real and a natural phenomenon that is *tightly anchored* to a biological reality found in the human brain. Thus, human brains are those specific "locations" in the physical world, where these two realities, the subjective mental reality and the objective neurobiological reality, although seemingly worlds apart, are intimately connected along a *unified metastable continuum* [11].

This approach is currently supported by most researchers working in the field [12-24] and is distinct from alternative ideas according to which consciousness is either a supernatural phenomenon that is entirely beyond the reach of science [25-28], or is a phenomenon found at the quantum level [29-32], or pervades the whole human body [33-37], or is instead present across the whole physical universe (so called panpsychism) [38-41].

If phenomenal consciousness is a biological phenomenon within the confines of the brain[2], then there must be a specific level of brain organization and a specific spatial–temporal grain in it where consciousness resides. In other words, we could expect that at the *lower* (in comparison with the phenomenal consciousness) level of brain organization there should be nonexperiential entities (some complex electrophysiological mechanisms) that function as the direct realization base of the phenomenal world. Additionally, phenomenal consciousness, being a real phenomenon, should have *causal powers*[3] distinct from the purely neurophysiological (nonphenomenal) realm [7]. However, to explain the 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 [43]. If it could be done, then we would be closer to understanding how it is possible that a particular level of brain functional organization manifests itself as a subjective world.

Before moving on, an important clarification should be made about the most frequent error/confusion that appears systematically when researchers try to explain consciousness: usually *constitutive* and *etiological* explanations are mixed. At the same time, they belong to different

[2] Importantly, this claim does not imply that consciousness is localized in some particular area of the brain, – on the contrary, all available experimental data point against such a possibility. The statement only postulates that consciousness is realized somewhere within the brain's reality rather than anywhere outside it [7].
[3] For the argumentation that to be real is to have causal powers see [42].

dimensions, and only one of them is interesting in the context of the present discussion. Constitutive explanation "looks" *downward* and describes what constitutes the phenomenon, while etiological explanation "looks" *backward* and specifies the causal pathway that either brought about or modulated the phenomenon [44]. In the case of consciousness, the constitutive basis includes such *immediately lower-level entities* on which consciousness as a whole is *ontologically* dependent (Fig. 1), meaning that consciousness could not exist without them to be present. In other words, a constitutive explanation describes immediate lower-level processes that as a whole is consciousness [7]. On the contrary, an etiological explanation considers the causal history or *pathway chain of events* that lead to consciousness and it is neutral about the constitutive entities (Fig. 1), because causal dependence does not entail ontological dependence [7]. Thus, as it is clearly stated by Revonsuo [7], "consciousness can in principle exist even in the absence of the entities and activities that make up its etiological pathway, while it cannot, even in principle, exist without the entities and activities that make up its constitutive basis." For the purposes of our discussion we are interested only in the constitutive basis of phenomenal consciousness.

In the following we will describe and analyse the functional architecture of the brain whose organization and dynamics could in principle be *isomorphic* to the architecture of a mind and thus constitute the subjective experience. However, it makes sense to look at 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. Once we have a clear description of the important principles of the higher phenomenal level, it will suggest what sorts of immediate lower-level neural phenomena might be closely associated with it and constitute it through the entangled complementary isomorphism principle [11].

2. Phenomenal consciousness level

Since a complete analysis of spatial–temporal organization of the phenomenal mind has been provided by us before [10,11], here we will concentrate on the principles that are the outcome of collective phenomena in any complex dynamical system – *criticality* and *self-organisation* – and which are important for situating the phenomenon of consciousness within universal laws of the physical world [1,24,45,46].

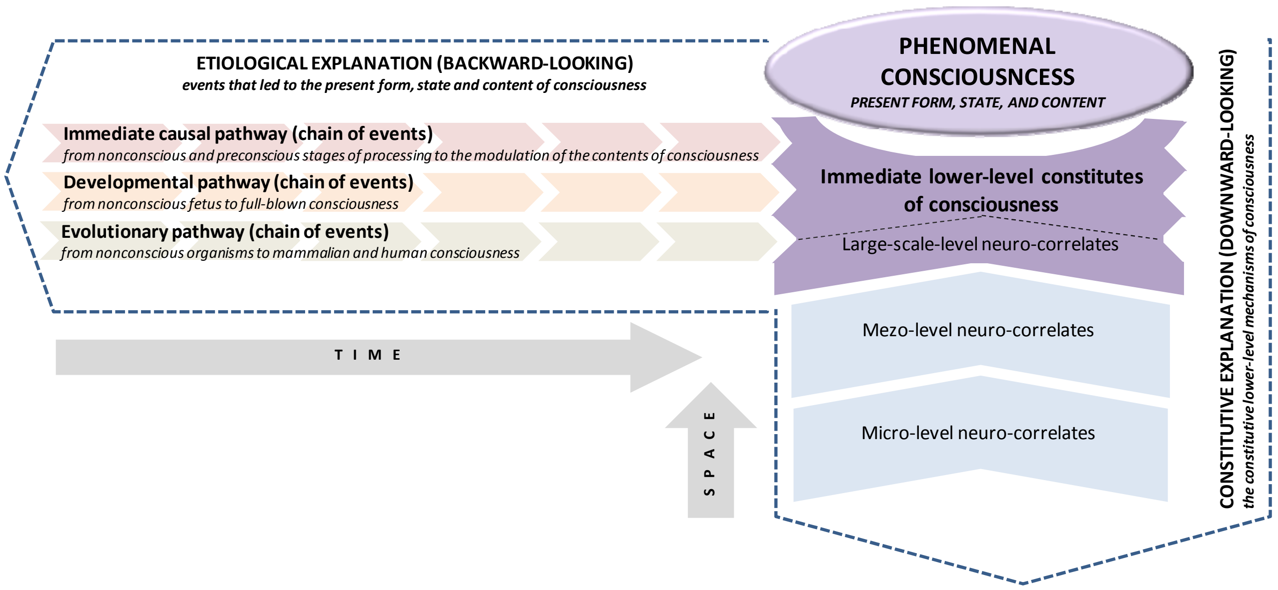

Figure 1. Etiological and constitutive explanations of consciousness. Etiological explanation describes the causal pathways that preceded the current state of the phenomenal consciousness and causally modulated it. Constitutive explanation describes the immediately lower level of organisation of the phenomenal consciousness that as a whole simply is the consciousness. Detailed description could be found in Revonsuo [7].

In physics, the notions of “phase space transitions”, “renormalization group” and “spatial–temporal separability principle” are powerful tools for interpreting complex systems phenomena involving many scales of space and time. According to Werner [24] the significance of these concepts is expressed in a detailed and systematic description of the emergence of many levels of new collective behaviors within complex systems, where each level is presented by its distinct macroscopic physics, organization, and laws as a new spatio-temporal pattern of reality [10].

The *renormalization group principle* [47] considers physical reality to be composed of a nested hierarchy[4] of levels, related to one another by phase transition, with each level representing a qualitatively new pattern of reality [51]. The *spatial–temporal separability principle* [52] means that the contents of any two (or more) regions of space–time, separated by a nonvanishing spatial–temporal interval, constitute different physical systems. In other words such systems possess their own distinct physical states and the joint state of such two (or more) systems is determined by their separate individual states [53]. Such macroscopic novel properties of a higher-level state have no referent at the microscopic lower-level; they create new physical states which call for new descriptions of physical reality [54]. The scale of space-time 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 [55,56]. In the

[4] The difference between non-nested and nested hierarchies is the following [48-50]: In a non-nested hierarchy the entities at higher levels of the hierarchy are physically independent from the entities at lower levels and there is strong constraint of higher upon lower levels. In a nested hierarchy, higher levels are physically composed of lower levels, and there is no central control of the system resulting in weak constraint of higher upon lower levels.

words of Werner [57], the macroscopic level can be viewed as an *abstract rendition* of the microscopic level (Fig. 2).

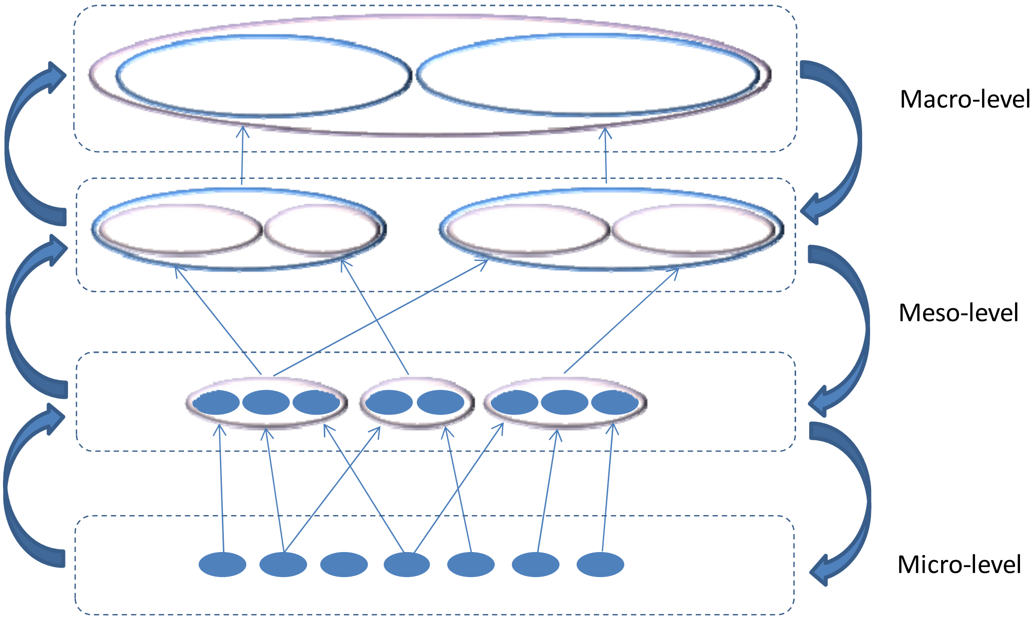

Figure 2. The nested hierarchy of levels in any physical system. Conceptually, the functional relations between and within levels of organization are often considered in terms of integration and differentiation where the larger scale is being 'slaved' to the smaller by some coupling function or circular causality. Each level presented by its distinct macroscopic physics, organization, and laws as a new spatio-temporal pattern of reality.

The cooperation between the individual parts at the microscopic level produces structures or functions at the macroscopic level by means of *self-organization* [58,59]. Self-organization is the means by which a system shifts into a new configuration, allowing it to offload the "unwanted" *entropy*. 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 [45]. Equilibrium is a thoroughly disordered regime, in which (a) there is *no* free energy and, therefore, *no* structure [60], (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 [45,61]. All closed systems tend toward greater entropy over time [60,62]. Self-organization is a potential property of open systems and it is this same entropy that provokes self-organization in the first place [60,63]. 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 in the least time possible [45,61]. 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* [62,64]. Thus, changes in entropy provide an important window into self-organization: a *sudden* increase of entropy in the least time just before the emergence of a new structure [45], followed by *brief* period of negative entropy (or *negentropy*) [65,66].

At all scales, the constraints among micro-elements must break or loosen to some degree before the system as a macrostate can change [67]. The system of a particular level is governed by fixed 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 state [45]. It is during these critical points that the collective variables, so-called order parameters, emerge at the macroscopic level. Since the number of order parameters is much smaller than that of the individual parts of the system, this allows for enormous *information compression* [59,68]. In general terms, order parameters determine the behavior of individual parts of a system at the microscopic level, while at the same time being maintained in their actions by cooperation of the individual parts [59,68]. Thus, we are dealing with *circular causality* (Fig. 2).

Can we find such nested hierarchy and associated complex dynamics in the architecture of a conscious mind? Substantial evidence from neurophysiological and cognitive investigations [69-72] infers that the phenomenal world has an immensely complex structure and fine nested hierarchical organization [7,73] (Fig. 3): at the bottom of such organization there is so-called *sub-phenomenal space* – a 3D, centered, bounded volume that represents the coordinate system[5] in which each location has the capability to realize a characteristic variety of self-presenting qualitative features [75-77]. Such phenomenal features (*qualities*) can be described in terms of the simplest phenomenal contents (sounds, colors, touches, emotions, tastes, smells, and so on) [78]. They are the identity, the "stuff" that experiences *per se* are made of. The next level of hierarchy is presented by carefully organized qualities that make up the patterns of experiences or *patterns of qualities* (Fig. 3). This level of a nested hierarchy of phenomenal mind makes it possible for the presentation of phenomenal objects at the next higher-level: the phenomenal patterns of different modalities (for example, visual and auditory) are spatially and temporally integrated, so that different features belonging to the same object are realized in the same location and temporal interval [10]. *Phenomenal objects* can be described as

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[5] We never subjectively experience the contentless coordinate system directly; we could know about it only through the relations among phenomenal objects. This was also confirmed by Damasio [74] using findings from experimental and clinical neuropsychology and neurophysiology data. He comes to a conclusion that this sub-phenomenal space is not self-presenting as such; however, it is the crucial aspect that allows self-presenting qualities (contents) to come into being.

complex patterns of qualities which are spatially extended and bounded with each other to form a unified item (Gestalt [79,80]) with a particular meaningful categorization (semantics [81]) immediately present for the subject. Any such object can be further organized hierarchically performing as parts (or features) of a more complex object, or alternatively decomposed into its constituent parts, all of which can be realized as separate simpler virtual objects independent of each other and with their own Gestalt and semantic properties (Fig. 3).

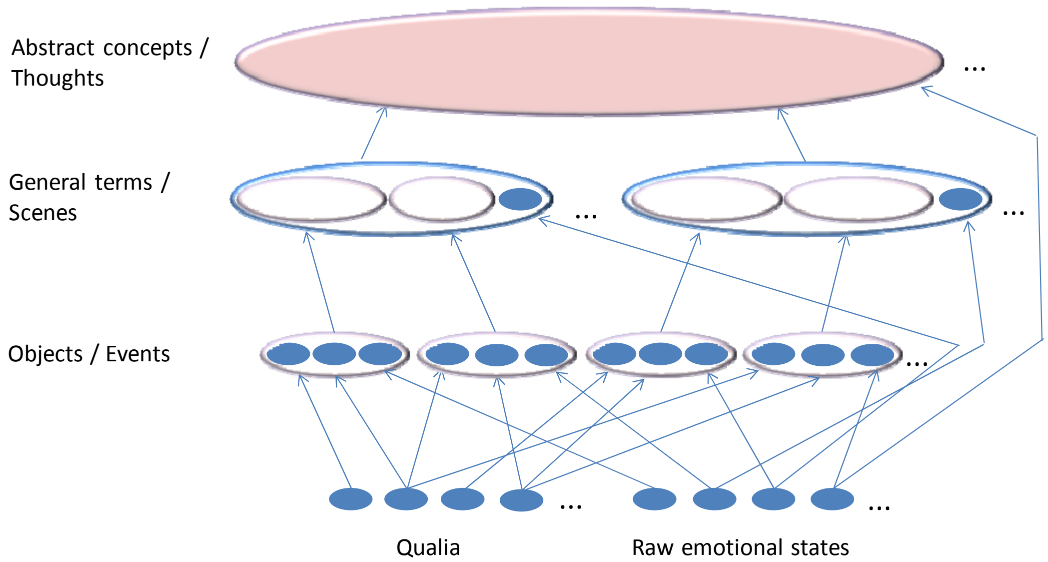

Figure 3. The nested hierarchy of subjective (phenomenal) experience (reinterpretation of Fig. 2). In this nested hierarchy the higher-level phenomenal entities are based on complex organization of lower-level phenomenal entities all the way down to the simplest phenomenal qualities.

Importantly, all levels of such nested hierarchical architecture of phenomenal consciousness (phenomenal qualities, their patterns, and full-fledged objects and scenes or concepts/thoughts) should be *simultaneously present* in order to establish spatial and meaningful relations among one another [11,73,77]. The phenomenal objects/thoughts that are not actualized at the moment (being preattentive or not in the focus of awareness) can be described as *raw* (or candidate) objects/thoughts that do not yet possess Gestalt and semantic properties, but rather some phenomenal undefined "stuff" [7].

Attention guides the actualization of full-fledged virtual, phenomenal objects/thoughts/decision on a one at a time basis, moving serially from one phenomenal object/thought/decision to another [82,83]. This process gives rise to a *stream of consciousness* [84]. According to James [84] the ever-changing stream of phenomenological consciousness could be presented as a rotating kaleidoscope where each momentarily stable pattern is a thought/image. Thus, such a stream 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 [23]: "the stream of consciousness is cinematographic rather than continuous, with multiple frames in coalescing rivulets" (see also [85-87]). Varela [88] 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 [89] introduces the notion of mental presentation, which is a subjective window of *presence*. Experimental evidence suggests it is also true for the cognitive and behavioral continuum, where each separate cognitive or behavioral act is expressed through a spatial–temporal integration of a certain number of operations, which are important and appropriate for the realization of these acts [90-92] (for recent reviews see [10,93]). 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* (RTP) [94] (Fig. 4).

Based on what we have described above, we may conclude that the phenomenal world has indeed a structure and dynamics that is compatible with physical understanding of any complex system. For example, a phenomenal mind (system's) state – conscious thought or image – may be described at a *microscopic level* in terms of its *constituent elements* (qualia, phenomenal patterns and objects). The same state can also be characterized at a *macroscopic level* – the conscious thought or image itself: that is how it appears to the subject through the "coarse graining" of the microscopic constituents by clumping them into ever larger *integrated aggregates* (see Fig. 2 and 3). However, to explain phenomenal consciousness in terms of universal physical laws [1,24,45] one needs to show that such principles as *criticality*, *self-organisation* and *emergence* govern the dynamics and organization of a conscious mind.

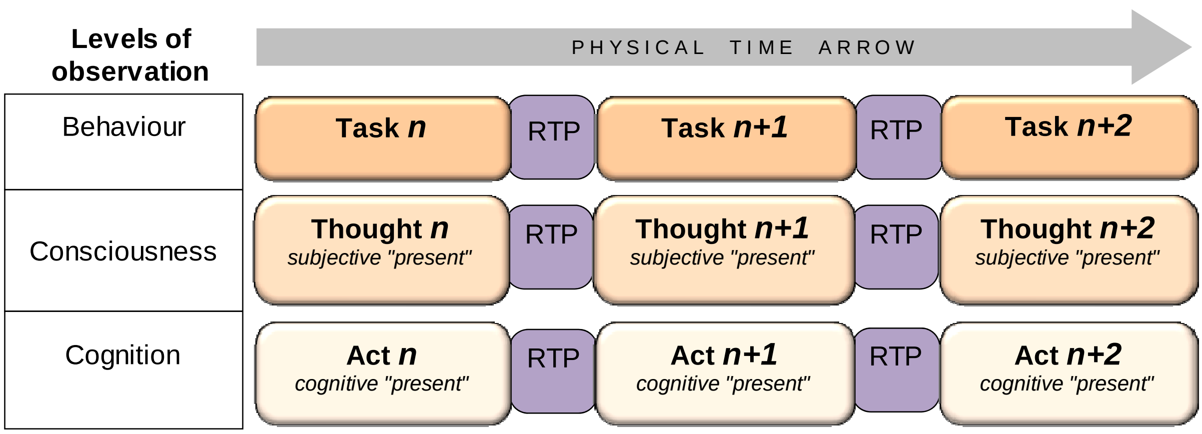

Figure 4. Schematic diagram depicting functional structures of cognition, phenomenological consciousness, and behaviour. As an example, the simplest case is shown, when cognitive, phenomenal and behavioural operations/acts coincide in time (in most cases these relations are more complex). Cognitive, phenomenological, and behavioural levels illustrate the ever-changing stream of cognitive/phenomenal/behavioural acts, where each momentarily stable pattern is a particular cognitive/phenomenal/behavioural macro-operation (thought/image/act) separated by transitive fringes (or Rapid Transitional Periods; RTP).

Careful analysis of cognitive and behavioural studies has identified that emergent cognitive structures arise *abruptly* from prior activity of the mind system [95,96], where complex conscious percepts/images/thoughts are built from primitive ones so that the semantic value of the complex states is determined by, and dependent on, the semantic values of the primitives [97]. The resulting structures reorganize the whole cognitive system's interaction with the environment and guide the behavior of the system [61]. Wertheimer [98] has proposed that the percepts or thoughts are not symbolic constructs to be produced by computation, but are instead a result of organization of physical forces. Similarly, Bickhard [95] has also suggested that the *physics of dynamical interactions* is the non-representational foundation from which representation of a percept, image or thought actually emerges. From a physical view, the flows of energy search for the paths of transduction and naturally select those that *consume free energy* in the least time [99]. This basic perspective means that any change in the cognitive system of mind, even consciousness and self, whether inherited genetically or imposed as neuronal network changes, will be possible because it contributes to the consumption of free energy [46].

As we have discussed in the beginning of this section, the self-organized emergence of a new structure is closely tied to the offloading of entropy, thus entropy and self-organization are intertwined [61]. In other words, self-organization is the means by which a system abruptly shifts into a new configuration, allowing the system to offload unwanted entropy [100]. It has been documented that spontaneous transitions in the mind happen at a *critical value* of a systematically varied behavioural/cognitive states [101], a property found to be consistent with Type-I intermittency [102], which is associated with a sequence of *critical events* with *power-law* distributed inter-event times. This as well as other studies pointed that the mental/cognitive system exhibits power-law behavior changes as it undergoes abrupt reorganization[6]. The breaking of constraints at all levels of a nested hierarchy increases the degree of power-law behavior (i.e., nested behavior increases) until the system reconfigures itself, – then the micro-elements are again constrained and power-law behavior decreases [61,104]. Dixon and colleagues, in a series of studies used a simple problem-solving task as a test bed [61,105-107] and have shown that spontaneous discovery (awareness) of a new relationship in a task marks the *emergence* of a new cognitive structure paralleled by a peak and subsequent drop in the *power-law* exponent [108]. Furthermore it has been shown that critical dynamics can indeed be related to optimal perceptual function [109]. It is concluded that such properties of the mind (multivariability and combinatorial power) are possible because they are spontaneously located at the *border of an*

[6] Different kinds of mental activity (i.e., perception, cognition, thinking, and imagining, as well as emotions and language) are transient and sequential (for detailed reviews see [93,103]).

instability; the same way as in thermodynamic systems at a critical point [1]. It is only in this state that the largest behavioral repertoire can be attained by the smallest number of degrees of freedom [110].

The discussed results are highly suggestive for the existence of a nested hierarchical organisation of phenomenal consciousness, whose dynamics has several statistical properties that are characteristic of self-organizing, fractal, scale-free, and self-similar systems. Although these results and conclusions follow the ideas put forward by Bak and colleagues [111-114], there is still much theoretical work to be done in order to integrate them with a physical substratum – brain.

3. Physical brain level

One important practical matter related to this challenge is to choose an appropriate level of physical (neurophysiological) explanation that captures a subjective phenomenal world [93]. As we have discussed in the Introduction section, this should be an immediately preceding level in the brain organization on which consciousness *supervenes* and to which it is *isomorphic* [10,11]. Several requirements must be met for such a level of brain functional architecture: (a) it should be one complementary part of the *metastable*[7] brain-mind continuum [Fingelkurts et al., 2009]; (b) its functional structure should be *isomorphic*[8] to the phenomenal structure of a mind [10]; (c) the *complexity* of such a level should be compatible with the complexity of phenomenal consciousness, because it has been documented that the two systems could share the same information only if they are equally complex [120-124]; (d) this level should have a *nested* hierarchical organization [73,125]; and (e) be relatively *independent* from the underlying neurophysiology, in addition to being "well-defined" and "well-detected" [10].

Now the question is: can we find such a level in the brain architecture, given that multiple regions within the neural hierarchy that are physically connected within the brain, as objectively observed, are not a physically nested system, in a way that a cell for example is physically nested within an organ [126]. From this observations it is not clear what in the brain constitutes the nested part of the hierarchy which support the isomorphic, complex, and nested hierarchy of the conscious mind. We propose elsewhere [125] that the **brain operational architectonics** (OA), centered around the *notion*

[7] Metastability was formulated by Kelso [115] within a classical model of coordination dynamics called the extended HKB [116] (HKB stands for Haken, Kelso and Bunz [117]). We have argued [11] that the metastability mode of brain–mind functioning introduces a hierarchical coupling (integrating tendency) between the brain and mind while simultaneously allowing them to retain their individuality (segregating tendency), thus exhibiting the main property of metastability principle – mutual co-existence of oppositional tendencies [118].

[8] By definition, two systems that are functionally isomorphic are, in virtue of this fact, different realizations of the same kind (for detailed discussion, see [119]). In other words, two different systems that are functionally isomorphic bring about the same function that defines the kind. 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 [10].

of operation, is the only brain level that satisfies all of these requirements. Approaching the notion of operation as a process lasting in time, present in both brain and mind, and considering its combinatorial nature (increasing complexity) it seems especially well suited for understanding and studying the mechanisms of how a conscious mind emerges from the brain [10]. The following subsection is dedicated to brain OA.

3.1. Operational Architectonics of the brain

As we have analysed in several publications [10,11,22,94], "operation" formally stands for a process (or series of acts/functions) that applied to an operand, yielding a transform, and which is limited in time (it has a beginning and an end). In broad terms it can be defined as the state of being in effect [127]. This definition provides a basis for discussing the relative complexity and compositionality of operations, where there is a more complex operation/operational act that subsumes the simpler ones [10]. In other words, each operation of this nested hierarchy of operations is not monolithic, – instead it has its own inherent fine structure (Fig. 5): every simpler operation exists within every other more complex one. Therefore operations should not be considered as objects in a conventional sense [128]. Rather, they should be seen as reciprocally entangled "autopoietic machines" [129], i.e., self-creating processes, or dissipative structures [130] that are nevertheless relatively stable and thus, only in that sense, could be conceived as distinct "objects".

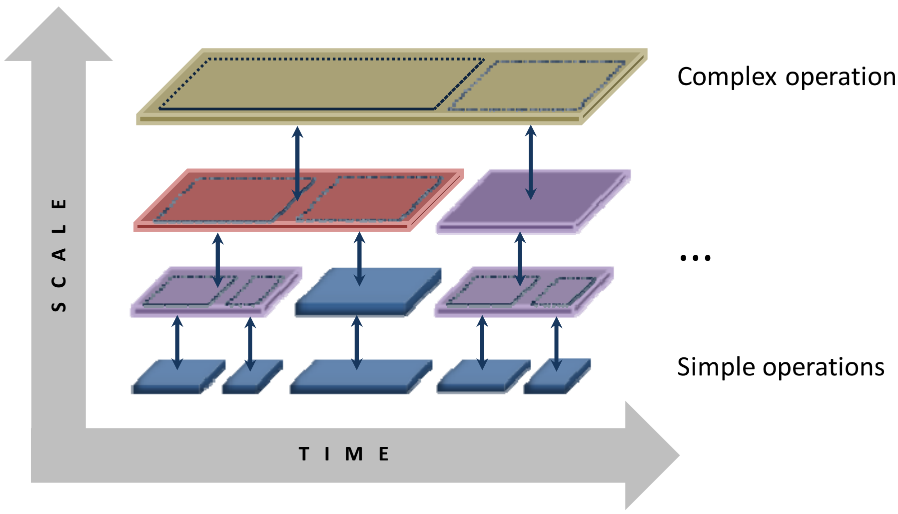

Figure 5. Schematic presentation of the compositionality of operations. Further explanations are provided in the text.

In this context, what might be the nature of such operational architectonics in the brain? In a series of publications [9-11,22,93,94,125] we have established a basis and developed a general theory of *brain operational architectonic* (OA), according to which the simplest mental/cognitive operations (responsible for qualia or simple computations) are presented in the brain in the form of *local 3D fields* produced by *transient functional neuronal assemblies*, while complex operations (responsible for complex objects, images or thoughts) are brought into existence by *joint simple operations* (temporal coupling of local 3D fields by means of operational synchrony, OS) in the form of so-called *operational modules* (OM) of varied complexity. Therefore, brain OA is presented as a highly structured and dynamic extracellular electric field nested in spatial and temporal domains [20,21] and over a range of frequencies [131], thus forming a particular *operational space–time* (OST) [10]. This OST exists within brain *internal physical space-time* (IPST) and is best captured by the electroencephalogram (EEG) measurement [23,132]. What is curious about the OST level of brain organization, is that on one hand it *intervenes between* IPST level where it literally resides, and on the other it is isomorphic to the experiential/subjective phenomenal structure of a mind – *phenomenal space-time* (PST). In other words, OST level has emergent properties relatively independent from the neurophysiological/neuroanatomical properties of the IPST level; phenomenal (PST) level supervenes on the operational (OST) level with one-to-one correspondence and ontologically it is inseparable from it (though it is separable from the brain neuroanatomical processes[9]) [10]. These relations are illustrated schematically on the Figure 6.

Below, we will illustrate how through EEG measurement one can study the OST level. We will analyze also the physical principles described in previous sections and that supposed to "work" at this level of brain organization, as well we will reveal functional isomorphism between EEG *structure* and the *structure* of phenomenal consciousness (PST).

At the *bottom* of the OST level there is a high multiplicity of local extracellular fields. 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 [23,21,132,146], they are expressed within local EEG signals in the form of *quasi-stationary segments*, each of which representing an envelope of amplitude modulation (so called a "common mode"/"wave packet" [147] or a "standing wave" [146]) in the neuronal mass under the recording electrodes. The more neurons transiently synchronize their

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[9] The relative independence of OST-PST metastable continuum from the neurophysiological (IPST) level can be illustrated as following: the structure, complexity and diversity of components of an OST (macro-level field phenomenon in the brain) can change while the number and variety of components of the underlying physical machine (brain IPST) remain fixed [133]. Moreover OST, as a complex field, could have "downward" causal influence on brain micro-scale properties altering the activity and plasticity of neurons, including network activity [134-138]. This allows PST to have some causal powers distinct from purely neurophysiological (non-phenomenal) realm: for example recent neuroimaging [139] and cognitive studies [140-142] have demonstrated that mental processes or events do exert "downward" causal influence on brain plasticity and various levels of brain functioning as well as on the sensory processing [143-145]. These data clearly show that phenomenal (PST) level is not just an epiphenomenon.

post-synaptic potentials the higher the amplitude of a common local field (Fig. 7) which is an indication of the collective behaviour at an emergent mesoscopic scale[10] – *neuronal assembly formation* [132,151,152].

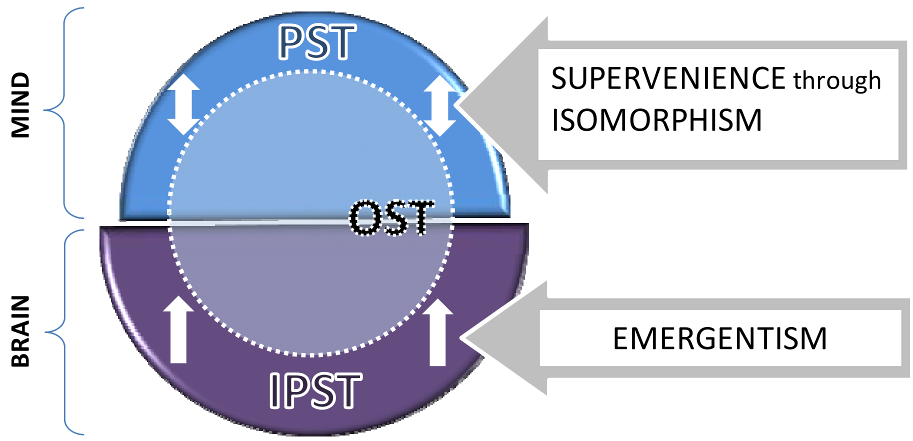

Figure 6. Different levels of the brain–mind organization and their relation to emergentism and supervenience. Electromagnetic brain field (OST level) is the emergent property of brain itself (IPST level). Phenomenal level (PST) supervenes on operational level of brain organization (OST). IPST indicates the internal physical space–time of the brain (violet colour); OST indicates the operational space–time of the brain (indicated by white puncture line); PST indicates the phenomenal space–time of consciousness (blue colour). In this model the OST level represents the constitutive mechanism of phenomenal consciousness; it ties the phenomenal (subjective) and neurophysiological (physical) levels together.

As generally agreed, the analytical amplitude of such local fields is mainly an indicator of the volume or *size* of neuronal assembly [132]. Because the transient neuronal assembly is formed to perform a particular operation/function of certain duration, this period (reflected in the EEG as a stabilized segment of quasi-stationary activity [93,94]) corresponds to the functional *life span* of the neuronal assembly or *duration of operation* produced by this assembly (Fig. 7). Even though each cortical area consists of several neuronal assemblies, their dynamics are easily and naturally separated based on a coordinated timing that is enabled by oscillations, which can be measured by *EEG frequency bands* [131,153,154,155]. Experimental studies have indeed shown that different frequencies appear to be related to the timing of different neuronal assemblies, which are associated with different types of sensory and cognitive processes (for a detailed overview, analysis and discussion see [155-157]). Thus neurons from the same network can be temporal members of different transient and functional neuronal assemblies at different instants of time [158]. Such a property of neurons relies on their capability to select appropriate information from incoming input depending on the context set by their own history and the activity of other neurons [159].

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[10] The emergent nature of local field potentials could be illustrated by the fact that they could show power-law scaling dynamics while the underlying neuronal activity per se does not [148-150]. Additionally endogenous local fields directly affect neurons in the neuronal assembly that generates these fields [134,138]. Mesoscopic electric activity may thus represent a dynamic order parameter that modulates and guides neuronal circuit activity within the assembly.

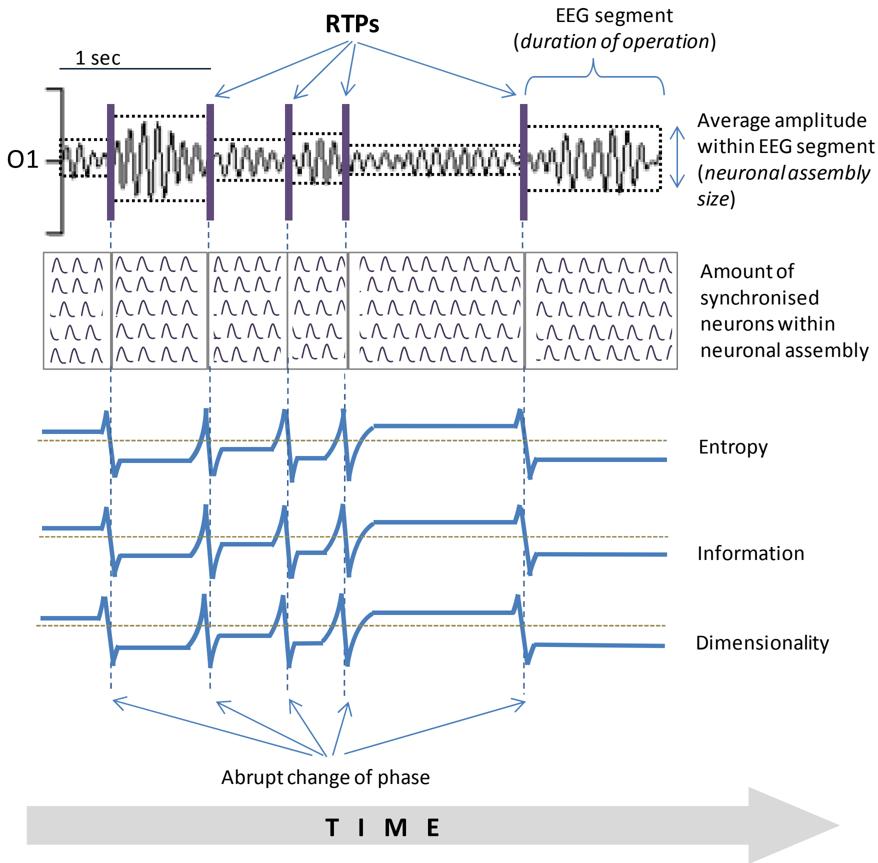

Figure 7. Schematic illustration of the neuronal assembly's dynamic and its relation to the EEG signal segments, a number of synchronized neurons, and thermodynamics of informational flow, entropy and dimensionality. RTP – rapid transitional processes. Local EEG signal (O1-left occipital location) is filtered in alpha (7–13 Hz) frequency band.

It has been proposed that EEG quasi-stationary segments (within which the local fields generated by transient functional neuronal assemblies are expressed) are equivalent to *simple mental operations* (phenomenal qualities, primary cognitive operations and emotions) [10,11,94]. Indeed, as it has been shown experimentally, 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 [160-165; for a review see 166] as well as under pharmacological influence [167-170] and various pathological conditions [161,171,172; for a review see 166]. Moreover, it has been documented that different neuronal assemblies' local fields correlate with different simple conscious percepts [23,173] and that in the absence of cognitive processing these specific transient neuronal assemblies do not appear [174] or are so small and short-lived that they are unable to support self-awareness and consciousness (as is the case in vegetative state patients) [175,176].

The quasi-stationary EEG segments within each local EEG signal are "glued" to one another by means of the *rapid transitional processes*/*periods* (RTPs)[11] (Fig. 7). RTPs are observed within a short-time window, when EEG amplitude changes abruptly [161]. Each RTP has very short duration in comparison to quasi-stationary segments length and can therefore be treated as a point or near-point [94,177,178]. Thus, RTPs (or abrupt jumps in EEG amplitude) are, in fact, the markers of boundaries between concatenated quasi-stationary segments (Fig. 7). The transition from one segment to another then reflects the moment of *abrupt switching* from one neuronal assembly's operation to another (see an example in [177]). Physically one could interpret such transition as the offloading of entropy and the emergence of a new structure of the system (neuronal assembly) [179,180]. Thus one could draw the following scenario that summarises the process (Fig. 7): the previous quasi-stable period (reflecting an emergent field of the collective behaviour of many neurons) was formed so that the neuronal assembly could perform an immediately present simple operation guided by either external stimulation or internal aim. Over time conditions naturally change and there is energy flow into an open system (neuronal assembly) [99,181]. This leads to an increase in entropy and the process continues until it reaches a critical threshold [45,61]. At this critical threshold – RTP, the old system dissolves under the stress of entropic fluctuations through a *sudden increase of entropy* [182] and *abruptly reorganizes itself* into a new system so as to offload entropy through negentropy [60,62] and thus meet the new requirement(s) – execution of a new operation (Fig. 7). The other two physical parameters of the system (neuronal assembly) follow the same dynamics during RTP: a sudden increase of *information* [183] and *dimensionality* [184], reflecting a critical instability and loss of constraints among micro-elements (neurons), followed by a rapid decrease in information and dimensionality, indicating the condition when the micro-elements (neurons) arrive at a new configuration, leading the system (neuronal assembly) to exhibit a different (new) structure (Fig. 7).

In the physics literature RTPs are referred to as *renewal* (or critical) events [185,186]; namely, the events that reset the memory of the system so that waiting times between two such events are all mutually independent, as proved by Allegrini et al. [187]. This latter property is in fact a mathematical definition of a well-known physical phenomenon of "intermittency" and is compatible with self-organized criticality in physical systems [111] and in the brain [24,57,188-192]. Recently, it has been documented that RTPs are indeed "crucial events" that correspond to phase-transition induced criticality [193] and have power-law distributed inter-event times [194]. Studies indicate that during such critical events local cortical networks (neuronal assemblies) are optimized for information transmission with maximum access to the number of potential metastable states, which confers a high

[11] In relation to nonstationary dynamics of EEG microstructure, the term RTP was first introduced in 1995 by Fingelkurts and Fingelkurts [160].

capacity for information storage [195,196]. Moreover, such criticality allows rapid adaptation of a neuronal assembly to very small exogenous perturbations [197]; namely it may undergo an extremely rich sequence of phase transitions, leading to the actualization of a sequence of dissipative structures [63] formed by wave packets [147]. This could have obvious selection advantages for a nervous system [198].

Detailed analysis of EEG intermittency has shown that scale-free brain activity, which comprises a significant portion of the spontaneous electrical field potentials, contains a rich temporal organization previously ignored as background noise dynamics [2,199]. Beggs and Plenz [200] propose to view such dynamics of local fields generated by neuronal assemblies as “neuronal avalanches” analogous to avalanches of physical systems characterized by Bak and coworkers [111,112,114]. As recently observed by Plenz [201], the totality of experimental, theoretical, and modeling studies suggest that “neuronal avalanches are the signature of brain function near criticality at which the cortex optimally responds to inputs and maximizes its information capacity”. Also, it has been documented that sequences of avalanches themselves organize as avalanches [201]. This suggests that there is no temporal or spatial scale, at which ongoing neuronal activity deviates from avalanche dynamics, and therefore we may expect similar behavior at the large-scale level of brain electrical field. Here we come to the macro-level of OST organization of the brain.

At the *macro-level* of OST organization, the brain OA is presented by self-organized and transitory spatio-temporal patterns formed by synchronized local fields that are generated by spatially dispersed local neuronal assemblies [10]. As it has been discussed above, individually each neuronal assembly presents only a partial aspect of the whole object/scene/thought/concept, while the wholeness of “perceived” or “imagined” is brought into existence by *joint (synchronized) operations* of many functional and transient neuronal assemblies in the brain (for a thorough discussion, see [10,11,202]). Indeed, operations performed by local neuronal assemblies may only be interpreted in terms of large-scale functional expression (a more complex operation) [203-205]. The recombination of local fields produced by neuronal assemblies in new configurations makes it possible to present subjectively a nearly infinite number of different qualities, patterns, objects, scenes and concepts – even those, with which we have never been acquainted before [10].

Because the beginning and end of discrete operations performed by local neuronal assemblies are marked by sharp changes (RTPs) in local EEG amplitude (Fig. 7), the *simultaneous occurrence* of these RTPs found in different local EEG signals within the multichannel EEG recording could provide evidence of *synchronization of neuronal assemblies* (located in different brain areas) that participate in the same functional act as a group (Fig. 8), e.g. executing a particular *complex operation* responsible for a subjective presentation of complex objects, scenes, concepts or thoughts [10,11,94].

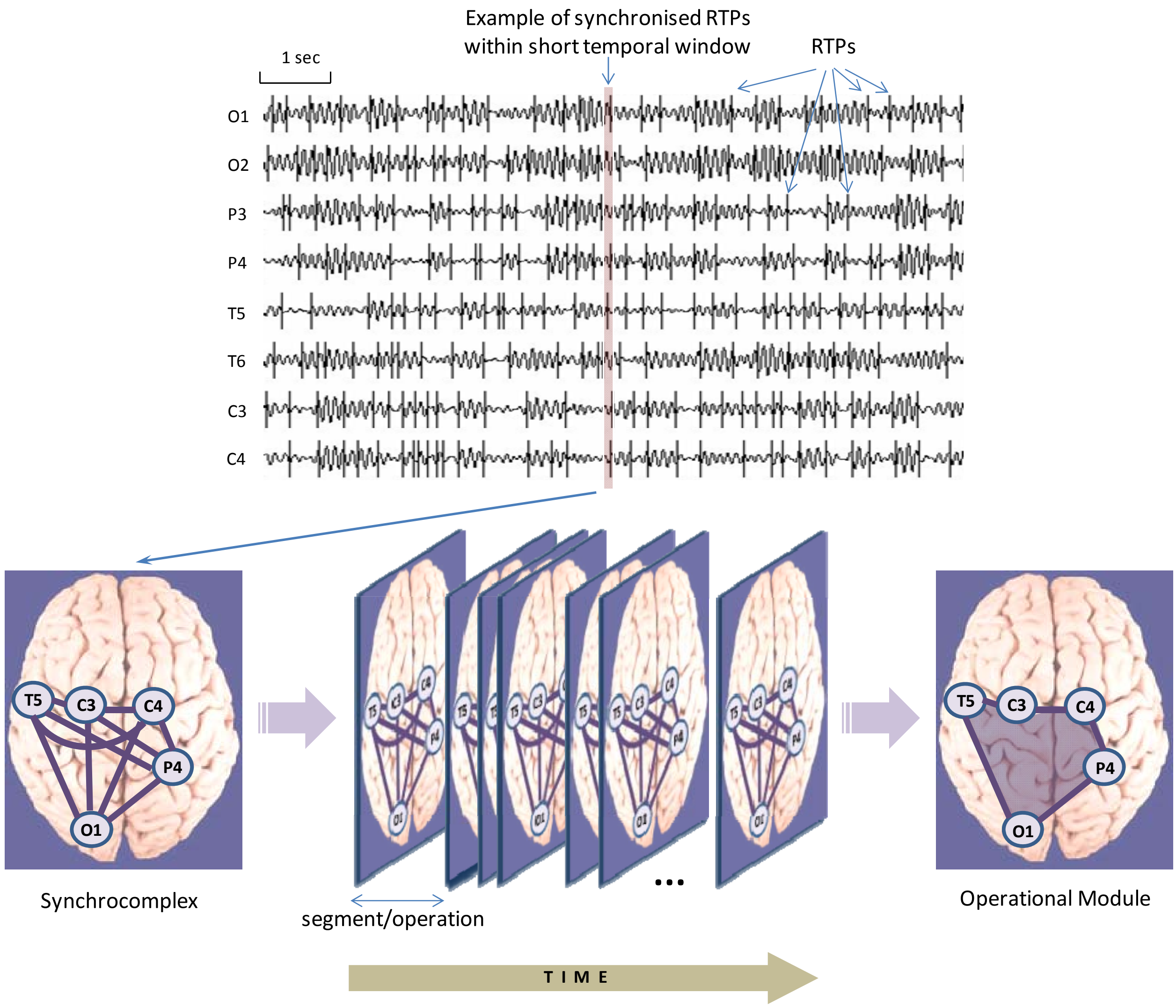

Figure 8. Schematic illustration of the synchronised rapid transitional periods (RTPs) and formation of operational modules (OMs). RTP – rapid transitional processes (boundaries between quasi-stationary EEG segments within the same EEG signal). Synchrocomplex – momentary synchronisation of RTPs among several local EEG signals within short temporal window of syncrhonisation. OM – synchronization of RTPs among several but always the same local EEG signals at the particular repetitive time instants (sinchronisation of quasi-stationary segments). O1 – left occipital EEG location, O2 – right occipital EEG location, P3 – left parietal EEG location, P4 – right parietal EEG location, T5 – left low temporal EEG location, T6 – right low temporal EEG location, C3 – left central EEG location, C4 – right central EEG location. All EEG signal are filtered in alpha (7–13 Hz) frequency band. Further explanations are provided in the text.

Fingelkurts and Fingelkurts [160] were the first who came up with this hypothesis and suggested a quantitative method for the estimation of this novel type of brain synchrony. The method was named "Structural Synchrony" (or index of structural synchrony, ISS) since it refers to synchrony between structures of local EEG signals, though qualitatively it estimates the synchrony among operations of multiple neuronal assemblies, thus it corresponds to an "*Operational Synchrony*" [161]. It is important to note that coincidence of RTPs among several local signals is related to a specific type of coupling –

the *synchronization of discrete events*[12] – which completely ignores the level of signal synchronization in the intervals (segments) between the coinciding RTPs [94,160,177]. Therefore, the described RTPs-based measure of brain synchrony, in contrast to conventional approaches, is free from similarities of the EEG signals in different channels. In this context, such an approach explicitly uses the definition of functional connectivity agreed upon in the neuroimaging community [207], which is defined as the temporal correlation between spatially remote neurophysiological *events* [208]. As it has been noted by Plenz [201], such a measure represents an unbiased estimate of synchronization, because in the absence of any knowledge about the underlying spatial organization of the involved neuronal assemblies, it uses temporal proximity of RTPs (transitive events) to estimate non-random interaction [177].

A set of EEG channels in which each channel forms a paired combination (with valid values of ISS) with all other EEG channels *within the same set* (meaning that all pairs of channels in a set have to have statistically significant ISS values linking them together) during a given instance of time forms a *synchrocomplex* (SC) (Fig. 8, bottom panel, left). The number of cortical areas (indexed by the synchronized EEG channels) recruited in a SC is described as "the order of areas recruitment" [160,161,177]. A sequence of the same SC types with the same "order of areas recruitment" during a given epoch of analysis gives rise to a completely new level of brain abstractness – *metastable brain states* [9], which we have called *operational modules* (OM)[13] [93,94,160,177]. In other words, the constancy and continuous existence of each OM persist across a sequence of discrete and concatenated segments of stabilized (coupled) local EEG activities (indexed by SCs) that constitute each particular OM (Fig. 8, bottom panel, right). Conceptually, the *continuity of any given OM exists as long as the set of neuronal assemblies located in different brain areas maintains synchronicity between their discrete operations* [22,93,177].

The notion of OM's operational space–time (OST) applies here [93]. Intuitively, OST of any given OM is the abstract (*virtual*) space and time which is "self-constructed" in the brain each time a particular OM emerges (Fig. 9). Formally, the OST concept holds that for a particular complex operation, the spatial distribution of the locations of a particular set of neuronal assemblies together

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[12] It should be noted here that the conventional and rather narrow neurophysiological definition of synchronization as two or many subsystems sharing specific common continuous frequencies is replaced here by the broader notion of a process, whereby two or many subsystems adjust some of their time-varying properties to a common temporal scale due to coupling of events [206].

[13] Metastability in the brain [9] refers to competition of complementary tendencies of cooperative integration and autonomous fragmentation among many distributed brain areas [17,22,94,118,209,210,211]. The interplay of these two tendencies (autonomy and integration) constitutes the metastable regime of brain functioning [9,118], where local (autonomous) and global (integrated) processes coexist as a complementary pair, not as antagonists [212]. 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 in order to execute the macro-operation [10].

with their synchronous activity at repetitive instants of time (indexed by SCs) comprises the OM (Fig. 8). These distributed locations of that set of neuronal assemblies are discrete, and their proximity as well as the activity in the "in-between area(s)", delimited by the known locations of neuronal assemblies, are not considered in the definition (*only the exact locations of a particular set of neuronal assemblies 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 [10]. This allows for a very detailed and statistically rich picture to be obtained on how locally synchronized groups of neurons form neuronal assemblies, that then self-organize in time and space in the form of transient cortex OMs of varying complexity (Fig. 9).

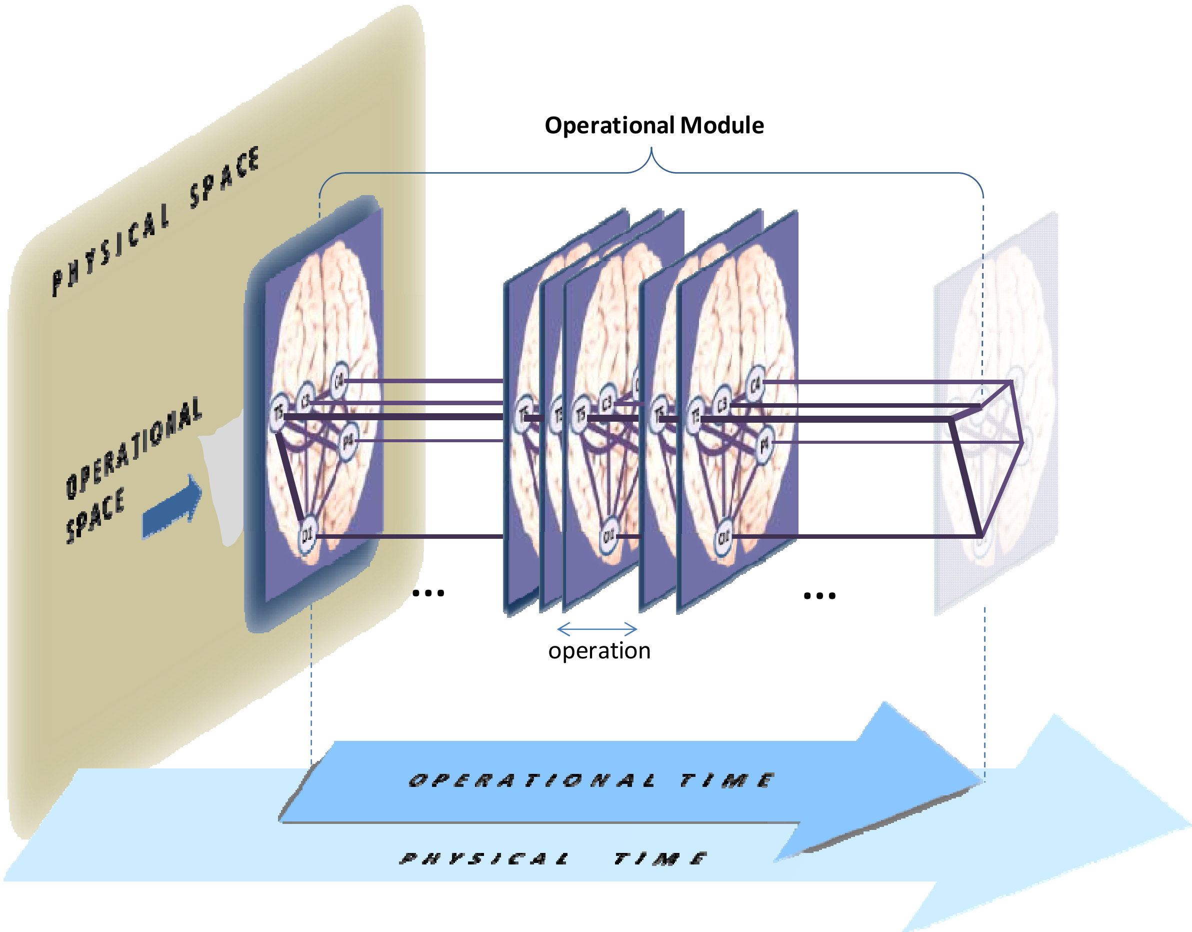

Figure 9. Schematic illustration of operational modules (OMs) and operational space-time (OST). Each OM exists in its own OST, which is "blind" to other possible time and space scales present simultaneously in the brain "system": all neural assemblies that do not contribute to a particular OM are temporarily and spatially "excluded" from the OST of that particular OM. As an example, it is shown that five neural assemblies located in particular cortical areas synchronize their operations within the same spatial–temporal scale, thus forming separate OM that has its own operational space–time (3D-object). Further explanations are provided in the text.

In this context, OMs lie, in some sense, between classical connectionist and process architectures. They resemble *connectionist networks* [213] 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 [81]. And yet, each OM is a *process*, since it lasts as long as several operations (which are produced by different neuronal assemblies) that have some continuity in time are synchronized among each other during a *given temporal interval* [10]. Following Lovecchio et al. [214] we may conclude that the best description of OMs in physical terms could be within "*extended criticality*" [215], because OMs being the "coherent critical structures" are "extended" and organized in such a way that they persist in space and time (Fig. 9).

Already first experimental studies [160-162,216-218] had shown that OMs (specific spatio-temporal configurations of stabilized segments among local EEG fields) do indeed exist, thus confirming the discovery of a new and previously unknown type of brain functional connectivity. It was found that such OMs are characterized by different order of recruitment of cortical areas: from any two to the whole cortex [160,217,219,220]. Furthermore, our research has shown [94,160-162,218], that *lower-level OMs* (being themselves the result of synchronized operations produced by distributed transitive neuronal assemblies) can further combine diversely with one another, both, within the same, and across different temporal scales, to form a more abstract *higher-level OM* in a nested hierarchy, thus constituting a more integrated experience [10,11]. In such operational architecture, each of the complex OMs is not just a sum of simpler OMs, but rather a natural union of abstractions about simpler OMs (Fig. 5). Therefore, OMs have a rich combinatorial complexity and the ability to rapidly reconfigure themselves, which is crucially important for the presentation of highly dynamic cognitive and phenomenal (subjective) experience [10,11]. Yet the opposite process is also possible, where any complex OM can be *partitioned* into a set of *sub-modules*, and to that effect each sub-module may be further decomposed into *sub-sub-modules*, striping these processes all the way down to *basic operations* (Fig. 5). It is suggested that such decomposition is responsible for a segmentation of our subjective experience and focused attention [10,11] and if the synchrony between local neuronal assemblies is lost completely, then consciousness fades, – this was recently confirmed experimentally on patients in vegetative state [175,176]. In other words, brain operational architecture that supports phenomenal consciousness consists of patterns of "*sandwiched emergence*" (that have been described for the emergence of complex societies [221]) and has the fractal property of hierarchical modularity, multi-scale modularity or, as Meunier and co-workers called it, "Russian doll" modularity [222].

Recent calculations have shown that *power-law statistics* do indeed govern the probability that a particular number of cortical areas is recruited into an OM (defined as the temporal RTP coincidences among different EEG channels) [187]. This ubiquitous dependency is characteristic for a fractal relation between different levels of resolution of the data, a property also called self-organized criticality [111]. It has been shown that OMs are driven by a *renewal process* with power index $\mu \approx 2$ [187,193,223], which is in line with Beggs and Plenz's [200] *avalanche dynamics* of cortex activity, though in this case at the large-scale level of brain OA organization – synchronization of local fields generated by multiple neuronal assemblies. In physics the value $\mu=2$ indicates a transition between two kinds of ergodicity breakdown, stationary and nonstationary, respectively [186,224]. Moreover, it has been shown that having complex networks at $\mu \approx 2$ provides ideal conditions for transmitting and receiving information [225]. Recently it has been confirmed that neuronal avalanches do indeed provide optimal conditions for *mutual information transfer* between stimulus and response [226] and allow the realization of a *large diversity of activity patterns* [201,227]. Considering that OMs are higher-order operations produced by synchronized lower-order operations performed by many neuronal assemblies along the cortex, with scale-free, power-law dynamics at many levels of description, one may conclude that the dynamic that guide them is the *same* and *independent* of the specific realization of brain OA level (from local neuronal assemblies to global spatio-temporal patterns – OMs). Freeman and Vitiello [147] proposed that the best mathematical tool to describe such "dynamic origin of long-range correlations, their rapid and efficient formation and dissolution, their interim stability in ground states, the multiplicity of coexisting and possibly non-interfering ground states, their degree of ordering, and their rich textures relating to sensory and motor facets of behaviors" is by applying the machinery of many-body field theory (see also [228]).

According to OA theory, the metastable OMs at an OST level somehow "freeze", and "classify" the ever changing and multiform stream of our cognition and conscious experiences [10], whereas the succession of complex cognitive operations, phenomenal images or thoughts (the stream of phenomenological consciousness [84]) is presented by the succession of discrete and relatively stable OMs, which are separated by rapid transitive processes (RTPs), i.e. *abrupt changes* of OMs (see Fig. 10). As it has been shown experimentally [161,162,167-171,216-219,220], at the critical point of transition in a mental state, e.g. during changes from one task/thought to another, the OM indeed undergoes a profound and rapid reconfiguration which is expressed through the following process [10]: a set of local bioelectrical fields (which constitute an OM) produced by transient neuronal assemblies located in several brain areas, rapidly loses functional couplings with one another[14] and establishes new couplings within another set of local bioelectric fields; thus demarcating a *new* OM in the volumetric OST continuum of the brain (Fig. 10). This process takes place not only at the level of

[14] This breaking apart of "micro-elements" brings about the nested structure that generates power-law behavior [61]. It allows the interactions to dominate the behavior of the system, at every scale [179,180].

simple (lower-level) OMs, but also at the level of complex (higher-level) OMs. Using such mechanism the brain can "rewire" itself dynamically and functionally on a milliseconds time scale without changing the synaptic hardware at the microscopic level [229,230]. This is why an OM is *relatively independent* from the underlying small-scale neurophysiological processes in the brain [10]. More specifically any OM is independent from intrinsic brain anatomical topology that determines which single neuron of a given anatomical circuit produces a particular spike pattern of a given temporal signature (for similar argumentation, see [20,231,232]).

In terms of critical theory of physics [62,64,233,234] and analogous to the formation of neuronal assemblies described above, within the RTP between two consequent OMs there is a brief period when the drastic and *abrupt increase* in degrees of freedom among participating neuronal assemblies is accompanied by a sudden increase in entropy [60], information [183] and dimensionality [184], followed by a *quick reduction* in the degrees of freedom of neuronal assemblies and rapid decrease in entropy, information and dimensionality (see Fig. 10). The second phase of such RTP is indicative of the *self-organization* of a new presentational state expressed in the form of a new OM within brain OST. In other words, during a critical transition point the macroscopic manifestation (OM or complex higher-order OM) is essentially based on a kind of abstraction from the original low-level (neuronal assemblies with their local electromagnetic fields or simple OMs), with all but those low-level features preserved (operations of neuronal assemblies or simple OMs) that now determine the novel macroscopic observable (either OM or complex OM) and presenting in fact a different biophysical state [45,57]. That is, the low-level elements (neuronal assemblies or simple OMs) can now explore different structural relationships with each other. When these low-elements arrive at a new configuration (OM or complex OM), then the whole system (OST-level) offloads entropy and exhibits a new structure which is suitable to present[15] the new complex operation, phenomenal image or a thought (Fig. 10; for a general conceptualization see [179,180]). Once the new OM (or complex higher-order OM) is initiated, the oscillation in each local neuronal assembly (or simple lower-order OM) that participate in the new OM is a standing wave and not a traveling wave, which is crucial for maintenance of stable spatial-temporal OM patterns (for a similar view see [146,147]). Based on the fact that brain consumes about 20% of basal metabolic energy [235], while it has only 2% of body mass [236], one may conclude that creation of OMs is energetically costly. This is so, because as it has been proposed by Freeman and Vitiello [147], the loss of free energy required to stabilize the dynamic brain patterns in the overall transit of energy carried to the brain by the arterial supply as glucose and

[15] The term "representation" may no longer apply to our description of cognitive or mental structure. As we have discussed in detail somewhere [10] the dynamical organization does not represent information to any mental faculty but, rather, directly embodies (self-presents) it.

removed by the venous return as waste heat should be minimized to avoid increases in temperature and pressure in the fixed volume and mass of the brain (see also [237]).

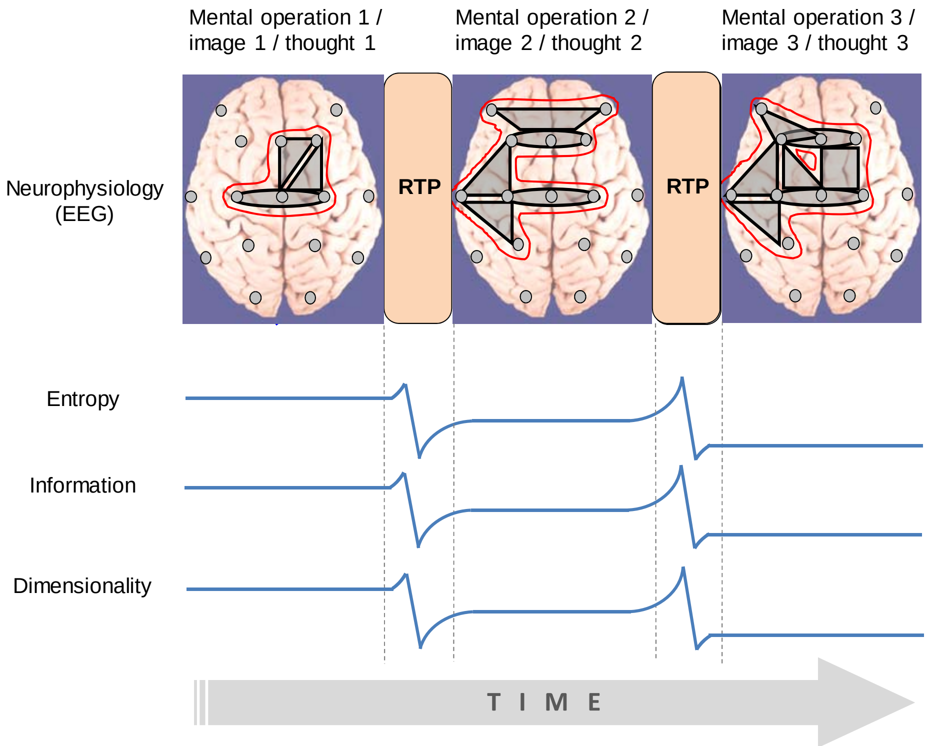

Figure 10. Schematic diagram depicting dynamics of operational modules (OMs) and its relation to thermodynamics of informational flow, entropy and dimensionality. Relatively stable complex (higher-order) OMs (outlined by the red line) undergo abrupt changes simultaneously with changes in a conscious cognitive task. Such abrupt changes are marked as rapid transitional periods (RTPs). Note, that during a RTP change the whole system (including its individual subsystems – simple lower-order OMs marked by grey shapes and neuronal assemblies – not shown) undergo dramatic reorganisation.

One of practical predictions from such OA of brain organization important for the clinical applications is a reasonable anticipation of a breakdown of OST structure and dynamics during pathology. How does an OST level of brain organization behave during a pathologic transformation? The antithesis of a scale-free (fractal) system (i.e., with multiple scales) is one that is dominated by a single frequency or scale. Therefore, breakdown of a fractal physiological control mechanism can either lead to a *highly periodic* output dominated by a single scale or to an *uncorrelated randomness*, – the same way as in thermodynamical systems of physics. At low temperature such systems are very ordered with only very large domains of equally oriented spins, a state that is practically invariant in time [1]. On the other extreme end, at very high temperatures, spins orientation changes constantly and rapidly, they are correlated at only very short distances and as consequently the mean state is invariant in time again [1]. In between these two homogeneous states, at the *critical* temperature, the thermodynamic systems exhibit very peculiar dynamics both in time and space – simultaneous existence of greatly correlated states which at the same time are able to wildly fluctuate at all scales [227,233,238].

Indeed, as our studies have shown [166], different pathological conditions of the brain or mind are characterized by an *excess* of couplings of operations and too rigid dynamics of such coupled operations or, on the contrary, by a *highly dynamic* processes of uncoupled short-lived operations approaching random dynamics. Similarly, when there are too few or too many OMs and their life-span is either too short or too long, then such conditions lead to the cessation of efficient cognitive and mental operation and consequently consciousness [175,176]. Thus it has been suggested that it is the dynamic metastable balance of integrated and segregated processes that is a necessary and sufficient condition to produce efficient cognitive activity (and eventually consciousness) [10,11,17,204,211,212,239-241]. The loss of such a metastable balance in favour of either independent or hyper-ordered processing leads to pathological states that give rise to neuropsychiatric syndromes constituting a particular disorder [166,168,241-243].

4. Conclusion

Understanding human consciousness requires the description of the laws of the immediately underlying neural collective phenomena, the nested hierarchy of spatiotemporal patterns of 3D electromagnetic fields produced by neuronal assemblies. Our analysis has shown that the structure, organization, dynamics, constituitive and causal relationships of such nested hierarchy of operational architectonics of brain activity are guided by the universal physical laws such as criticality, self-organisation and emergence. The proposed operational architectonics framework depicting the mechanisms and dynamics of consciousness allows us to literally “see” how the phenomenal (subjective) level is instantiated in the brain. According to this framework, if the operational level of brain organization (as a whole) is taken away, the phenomenal world ceases to exist.

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