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REVIEW

Consciousness related neural events viewed as brain state space transitions

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Abstract This theoretical and speculative essay addresses a categorical distinction between neural events of sensory-motor cognition and those presumably associated with consciousness. It proposes to view this distinction in the framework of the branch of Statistical Physics currently referred to as Modern Critical Theory (Stanley, Introduction to phase transitions and critical phenomena, 1987; Marro and Dickman, Nonequilibrium phase transitions in lattice, 1999). Based on established landmarks of brain dynamics, network configurations and their role for conveying oscillatory activity of certain frequencies bands, the question is examined: what kind of state space transitions can systems with these properties undergo, and could the relation between neural processes of sensory-motor cognition and those of events in consciousness be of the same category as is characterized by state transitions in non-equilibrium physical systems? Approaches for empirical validation of this view by suitably designed brain imaging studies, and for computational simulations of the proposed principle are discussed.

Keywords State space · Consciousness · Emergence · Neural oscillations · Cognition · Reductionism · Networks

Introduction

Two current trends in the discourse in Cognitive Neuroscience and its participating disciplines are, first, the realization that Cognitive Systems are intrinsically dynamical systems (Giunti 1997; Port and van Gelder 1995; van Gelder 1998) which function in interaction with the environment and as embodied actors (Varela et al. 1995; Chiel and Beer 1997; Thompson 2007); and, second, the formulation of the Global Workspace Model by Baars (1988, 1997, 2002): both have become reference points for theory formation on brain-mind relations. Baars' "cognitive theory of consciousness" postulates a multitude of special purpose processors, almost always unconscious. Coalitions of such processors can gain access to a limited capacity global workspace for integrating competing and cooperating input and for recruiting additional processors for dealing with novelty and problem solving. All this occurs under the auspices of certain 'contexts' which are themselves coalitions of processors.

In the following, I will draw on the conceptual resources of Dynamical System Theory and the methodological tools of Complex System Science for proposing that considerations of certain aspects of statistical Physics, and of a new outlook on the character of explanation in Physics, will broaden the conceptual base of Cognitive Neuroscience. Its antecedents are the investigations of state transitions at the mesoscopic level of nervous systems by Freeman (2005a), and the studies of pattern transitions in brain electrical activity and behavior, conducted in the spirit of Coordination Dynamics (Kelso et al. 1992; Wallenstein et al. 1995; Jirsa 2004; Kelso and Engstrom 2006), and linking global brain events and behavior. However, in distinction, I will emphasize that aspect of state transitions from one level of a hierarchical system to the next, which are associated with changes of scales and dimensionality, and the origin of qualitatively new properties at the next higher level. Atmanspacher and Kronz (1999) have examined some of the relevant ontological and epistemological issues.

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The following sections present a brief sketch of observational and conceptual benchmarks from the Neurosciences, limited only to such aspects in recent literature and current debates as are required for clearing the way to characterizing the theoretical framework which I here propose. This will be followed by an outline of the conceptual framework of relevant aspects of Statistical Physics as basis for considering the conceptual and heuristic implications of viewing the Neuroscience of Cognition and Consciousness in this framework. For consistency, I will adopt the convention in Statistical Physics for designating 'micro-' and 'macro-state' as two levels of a system's organization, prior to and after state a transitions; thus, in the present context, 'microscopic' stands for the neuronal brain configuration associated with cognition, and 'macroscopic' for that of conscious states.

Oscillatory neural activity

Oscillatory neural activity is widely accepted as subserving communication among cell assemblies across a wide range of spatial and temporal scales (Basar et al. 2004; Buzsaki 2006). Pursuing Freeman's (1975) notions of "mass action" in the Nervous System, Varela (1995) subsumed the result of a large number of investigations of their own and of other authors, at first, under the notion of Resonant Cell assemblies, and subsequently under the idea of the Brain Web (Varela et al. 2001). Thus originated the Research Program of the Dynamic Core (Le VanQuyen 2003) at meso- and macroscopic scales. Neuronal oscillatory patterns comprise spike discharges and local field potentials (LFP). Their role is thought to be twofold: dynamically constituting functionally interacting neuron assemblies, and acting as communication links in virtue of phase synchrony. These generalizations rest on a wealth of analytical, numerical-computational and empirical data: mechanism of oscillatory coupling are discussed in great detail by Pikovsky et al. (2001), and, amongst others, also by Tass and Haken (1996) and Mirollo and Strogatz (1990). Mutual synchronization is reviewed in detail in Chapter 6 of Mikhailov and Calenbur (2006). Onset of oscillations are often viewed in terms of Kuramoto's self-organizing synchronization (Acebron et al. 2005).

From among the numerous experimental and clinical observations of functional roles of oscillatory activity under a large variety of circumstances, I cite merely a few recent sources, by way of illustration and with pointers to prior reports: Schnitzler and Gross (2005) review normal and pathological oscillatory communication in the brain. Bressler and Kelso (2001) underscore the metastable dynamics and coordination of cortical areas in relation to phase relationship of oscillatory activity. Bypassing the voluminous literature of the 1980s and 90s on a putative role of oscillatory neural activity for perception and cognition, I mention here merely two recent contributions on their role in attentional mechanisms: Saalman et al. (2007) show that selective attention in a visual masking task is associated with synchronizing neuronal activity in the monkey's parietal and mediotemporal cortical areas, and Buschman and Miller (2007) report that synchrony of neural discharges between prefrontal and posterior parietal cortices occurs at different frequencies which apparently signify different modes of attention, supplementing earlier brain imaging data on anti-correlation pattern of spontaneous activity in ventral and dorsal attentional system (Fox et al. 2006). In simulation studies, Bibbing et al. (2002) established a purely cortical mechanism capable of generating synchronicity at beta range frequencies, potentially acting in parallel to the thalamo-cortical and cortico-thalamic interactions for long-range synchronization via recurrent, reciprocal neuronal connections (also referred to as "reentry", Sporns et al. 1989).

Long-distance synchronization of brain activity in human subjects engaged in perceptual-cognitive tasks was reported, among others, by Rodriguez et al. (1999). These and the numerous related observations can now be supplemented with the findings of Koenig et al. (2005): combining electroencephalographic records with functional magnetic resonance imaging identified transient "binding" (see below) between different brain regions through synchronized oscillations. Synchronization of neural activity in disparate cortical regions may then be thought of as a mechanism for constituting transient functional neurocognitive networks. At least in one instance, it was possible to demonstrate in the awake monkey that oscillations in the beta frequency range carry Granger causal influences from primary somatic sensory and inferior parietal cortices to motor cortex (Brovelli et al. 2004).

The 'communication-through-coherence' hypothesis of Fries (2005) proposes to close the gap between the suggestive evidence for the functional efficacy of neuronal oscillatory activity on the one hand, and a detailed understanding of its mechanism, on the other: phase-locking among oscillations of neuron assemblies is thought to enable their effective communication by acting as windows of frequency-specific interaction, as a kind of gating mechanisms. This could constitute an intricate dynamic communication structure for selective routing of neuronal activity. The hypothesis can draw on the fact that gamma-band synchronization of synaptic inputs enhances their effective synaptic strength (Salinas and Sejnowski 2001), and is also supported by the recent finding of Womelsdorf et al. (2007): in a set of elegant experiments on the cortices of awake cats and monkeys, the precise timing between rhythmic activity of neuronal groups determined the strength of their mutual interaction, presumably due to frequency specific rhythmic modulation of synaptic inputs. Hence, effective connectivity can be regulated upward and downward through synchronization, depending on the phase relation. One can readily visualize how the temporal and spatial pattern of synchronization imposes a distributed pattern of synaptic gains (a grid of traffic lights, if you will) on the infrastructure of anatomic connections, with the effect of dynamically modifying interactions among neuronal groups. The significance of this point of view will become even more apparent in later sections if this essay.

Although the focus of interest is generally on the synchronicity (phase locking) of oscillatory interrelation among neuron assemblies, alternating periods of asynchronous coupling are of equal importance for it is these which make dynamic re-configuration of communicating neuron assemblies possible: an interrupt mechanisms, as it were, for enabling swift adaptive changes by shifting coherence patterns from one communicating cell assembly to another (Breakspear et al. 2004; Friston 2000). The capacity for alternation between synchrony and asynchrony is also one aspect of the metastable coupling/uncoupling of integration and differentiation in coordination Dynamics (Kelso and Engstrom 2006). Simulated adaptive network controllers evolve towards increasing “fitness” with shifting the dynamical integration/differentiation balance (Seth and Edelman 2004), reflecting changes in mutual information of interacting neuron pools which was originally proposed as measure of brain complexity (Tononi et al. 1994) and index of consciousness (Tononi and Edelman 1998). However, it now appears that neither this nor any other thus far considered measure of the brain’s multidimensional complexity adequately reflects the temporal and spatio-temporal dynamics of neural systems (Seth et al. 2006).

The coordinating function of neuronal oscillatory activity is traditionally described in terms of the intuitively appealing notion of “binding” (von der Malsburg 1981/1994, 1999) between neuron pools. The salient feature of this intuitive notion can now be stated in more specific terms. In a series of papers, Maye and Werning (Maye 2003; Maye and Werning 2004; Werning and Maye 2006) demonstrated feature compositionality in networks of coupled oscillators: oscillators which represent objects that share features do also synchronize. Thus, features are ‘recognized’ as constituents of objects, and pass their causal properties (upward, so to say) on to complex (object) representations. In this sense, synchronizing oscillators have the capacity for compositionality.

How synchronicity is mediated between disjoint neuron assemblies is the subject of the next section.

On brain network connectivity

Earlier investigation of the brain’s network structure and connectivity patterns (e.g., Mesulam 1998) are now enriched by the insights into the statistical mechanics (Albert and Barabasi 2002), the development (Dorogovtsev and Mendes 2003) and structure and function (Newman 2003) of complex networks. Investigations of Hilgetag et al. (2000) and others generated a wealth of neuroanatomical data which, together with the application of methods of graph theory (Bollobas 1985) and computational analysis of network configurations (Hilgetag et al. 2002) came to constitute the field of Computational Neuroanatomy (Sporns et al. 2000). It is concerned with establishing the relations between classes of network connectivity, network dynamics, and measures of the brain’s complexity. One of the principal objectives of research in this field is to identify the conditions under which structural-anatomical connection patterns become functionally engaged, and what the properties of the resulting functional networks are.

For the purposes of the following, it suffices to consider two classes of networks: small-world, and scale-free. The characteristic connection topology of the former class of networks was first described by Watts and Stogatz (1998) and Strogatz (2001). It consists in the prevalence of highly clustered, short (near- and next-near-neighbor) connections over long range shortcuts to distant nodes. Their connectivity is intermediate between completely regular and completely random, and their short characteristic path length accounts for what is described by the evocative term of “cliquishness”. Scale-free networks, on the other hand are characterized by a scale-free statistical distribution of numbers of edges per network node, which implies their being poised towards critical state transitions.

In a recent review, Sporns and Zwi (2004) reaffirmed and extended the previously established small-world characteristics of the anatomical inter-area cortical connection patterns, as has Humphries et al. (2006) for the structure of the brain stem reticular formation. Sporns (2006) also compared brain organization at different levels of scale, ranging from local neuronal groups to patterns of intra- and inter-area connections up to extended cortical systems, and determined that it displays self-similarity, i.e. a fractal patterns, that is, the pattern of network connectivity is identical at all levels of the central nervous system, safe for changes in scale. The small-world properties of anatomical brain networks can be viewed as a developmental compromise between keeping the ‘cost’ of wiring length small, and yet secure also the efficiency of long-distance connections. Within complex networks, recurring patterns of interconnections form ‘motifs’ which appear to function as elementary building blocks (Milo et al. 2002).

A small repertoire of such structural motifs can also be identified in brain networks (Sporns and Koetter 2004).

Network topology and network dynamics are decisively interdependent (Grinstein and Linsker 2005). Therefore, it is essential to ask: what role does the functional brain network architecture play in brain dynamics?

On theoretical grounds, simulation studies attribute significance to features of small-world networks insofar as it supports fast response and temporally coherent oscillations of the network nodes (Lago-Fernandez et al. 2000; Wang and Chen 2002). This is thought to be of relevance for 'feature binding' (Masuda and Aihara 2004), efficiency in local and global information exchange (Latora and Marchiori 2001; Bassett and Bullmore 2006), and for facilitating global synchrony of coupled phase oscillators (Watts 1999; Barahona and Pecora 2001). In general, this collective behavior presupposes the non-locality of at least some connections (Gade and Sinha (2006): a requirement which, of course, small-world networks meet. However, small-word networks (graphs) comprise several classes depending on their vertex connectivity; one of them is identical with 'scale-free networks' (Amaral et al. 2000; Newman 2000). Thus, labeling a network merely as "small world" is not necessarily a complete characterization of its functional repertoire.

Observational data obtained with PET and fMRI imaging methods and their interpretation in terms of network theory have generated important insights into intra-area functional connectivity, and its role for human brain function, both in a so-called 'resting' state and states of experimenter-elicited activity. However, 'Resting State' needs to be taken with a grain of salt (Gusnard and Raichle 2001). Consider, for instance the brain activity of 'wandering minds' (Mason et al. 2007).

Measuring correlations between "voxel" in MGE's of brains in subjects carrying out a finger tapping task, Eguiluz et al. (2005) identified functional brain small world networks with scale-free properties. Stam (2004) was guided by the idea that network synchronization at different frequency bands may reflect functional differences; in no-task, eye closed conditions, he found that connectivity patterns below 8 Hz and above 30 Hz display small world properties, but they did not in the alpha—and beta range. Frequency dependent difference in functional network connectivity were also found by Salvador et al. (2005a, b).

A major methodological advance in the form of discrete wavelet decomposition of fMRI time series of the human brain (Bullmore et al. 2004) in combination with graph theoretical methods make it possible to extend the frequency band of analysis over a physiologically relevant range. Achard et al. (2006) found small-world topology of sparse connections most salient in the frequency range of 0.03–0.06 Hz. The degree distribution of the highly connected hubs of uni- and heteromodal association cortex reflects an exponentially truncated power law. Extending the scaling regime up to 75 Hz, Bassett et al (2006) identified functional networks with small-world topology and critical dynamics over a frequency range from 1 to 75 Hz. Connectivity between brain regions varied with the frequency range, long range functional connectivity in the resting state being stronger at low frequencies. With task performance, long range functional connections emerge more strongly at higher frequencies, associated with a significant motor task related increase in characteristic length scale of edges in high frequency motor networks. The network dynamics is thus seen as supporting task-related reconfiguration, potentially also drawing on the reserve of uncommitted connections in the otherwise sparse networks. Adaptive and rapid reconfiguration is possible because the synchronizability of the networks is in all states and at all scales close to the order-disorder transition. Under more complex conditions, tested as 'task sets' which require initiation, maintenance and adjustments, a fronto-parietal and a cingulo-opercular network participate, operating independently and on different time scales (Dosenbach et al. 2006, 2007; Fair et al. 2007); their life-span development is associated with decrease of short-range, and increase of long-range connections (Fair et al. 2007).

Computational simulations of relations between network structure and activity patterns add insights into an amazingly intricate and specific dynamics in the temporal and spatial domain. In a network model reflecting segregated regions and interregional pathways of the macaque cortex, based on the database CoCoMac (Koetter 2001), Honey et al. (2007) simulated the distribution pattern of spontaneous (i.e. in absence of external stimulation) cortical dynamics. The neuronal dynamics within each of the cortical regions was emulated as a neural mass model with self-organizing oscillations, serving as a spontaneously active motor, as it were, that drives the entire system. Interregional interactions were measured as Transfer Entropy (Schreiber 2000) and transient synchrony between pairs of regions was expressed as phase locking value (Lachaux et al. 1999). The cortical 'resting' state displayed a rich temporal structure at multiple time scales: at time scales of 10 Hz, the system dynamics consists of multiple metastable states; at lower frequencies, fluctuations in the strength of correlated coupling occur, with regions participating in one or the other cluster in an anticorrelated manner. The group of Zhou and associates (Zhou et al. 2006, 2007; Zemanova et al. 2006) performed a comparable study with similar methodology, based on a model of the cat brain. Their results underscore the sensitive dependence of the network organization into functional synchronizing communities on the degree of coupling, and on the network topology.

The observations cited in the foregoing section point to the brain's extraordinary capacity for routing the oscillatory activity of neuronal centers into different channels, and over different ranges to different destinations, depending on the oscillation frequency of the signals they convey: a communication system, dynamically structured by the property of the signals it carries. Equally amazing is the interplay between the brain's small-world network feature supporting synchonization, and its being near criticality (the later also associated with scale invariance of node degrees which, in the theory of Albert and Barabasi (2002), may be due to local re-wiring, addition or removal of nodes): while criticality favors state transitions, it also constrains the small world synchronizing propensity of the networks, thus preventing 'seizures-like' loss of network frequency specificity (Percha et al. 2005): a proper balance of opposing trends must be maintained.

Albeit held in balance, the scale-free aspect of the functional justifies Chialvo's (2006) evocative expression of " the brain near the edge". This is also evident from appropriate analyses of the encephalogram. In numerous publications, Freeman (2004a, b, 2005a, b, 2006) provided solid support for the view that the brain state space dynamics is poised towards a global state of self-organized criticality which affords the possibility for virtually instantaneous reorganization upon changes in external or internal variables. Evidence for scale-free brain dynamics of EEG as signature of self-organized criticality was also obtained by Linkenkaer-Hansen et al. (2001), Gong et al. (2003), and Stam and de Bruin (2004). Transcranial magnetic stimulation was shown to induce switches between two distinct modes of behavior (Meyer-Lindenberg et al. 2002). The totality of these observations is also consistent with qualitative predictions from Baars' model which envisions the possibility of abrupt activation of a Global Workspace under appropriate conditions. Werner (2007a) attributes this abrupt activation to self-organized criticality.

On cognition and consciousness

This section singles out those aspects of cognition and consciousness that are relevant for the proposed brain the state transition. They are: their categorical distinction; the nature of neurophysiological process plausibly associated with consciousness; and the sudden and abrupt onset of conscious events.

In the first place, the reactive behavior of organism's sensory-motor interaction with the environment must be clearly differentiated from the qualitative subjective states and processes of sentience and awareness; the latter having their own, distinct Ontology (Searle 2000). In Neuroscience, Lamme (2003) and Dehaene et al. (2006) assembled several lines of evidence which converge to differentiating conscious from unconscious processing, as do the findings with blind sight (Weiskrantz 1986) and semantic priming (Dehaene and Nagache 2002). I adopt Searle's (l.c.) notion of the state of wakefulness as basal (background) consciousness, a kind of unified field, presumably identical or overlapping with the condition of vigilance in the terminology of Dehaene et al. (2003). Specific sensory events would then punctuate, as it were, the steady state of the unified field, as the basis of discrete subjective experiences. This notion of discrete events in Consciousness tallies with observations of Fingelkurts and Fingelkurts (2001, 2005, 2006) of discontinuities in the EEG which they identify as transient operational brain microstates, signaling shifting activation of neuronal networks. Independently, Lehmann and associates (1998, 2006; Michel et al. 1992; Koenig et al. 2005) characterized at the brain-scale level a segmentation of global brain electrical activity into discrete units which are interpreted as functional microstates of the brain. They may correspond to basic constituents of conscious events. Detailed quantitative analysis of these brain electrical microstates identified a repertoire of classes of brain topographic maps of which Koenig et al. (2002) determined normative data for resting EEG, varying with differences in age-dependent developmental stages of cognitive styles. Werner (2007a) suggested that the records of these functional microstates may reflect self-organizing state transitions in neural circuits.

In an extended series of studies designed to delineate conscious from non-conscious brain processing in neurophysiological terms, Dehaene et al. (1989, 1991, 1997, 2003; Changeux and Michel 2006), developed the hypothesis of the Neuronal Global Workspace. Two prominent features emerged: one, that events in consciousness are predicated on a 'brain scale' co-activation of multiple brain areas in reciprocal interaction; and, second, that this coactivation abruptly "ignites' (in the apt terminology of Changeux) because of "self-amplifying recurrent activity" in widely distributed cortical regions. Accordingly, Dehaene et al (2006) consider conscious perception to be systematically associated with surges of neural activity in parieto-frontal cortical regions Edelman (2003) also considers dynamic reentrant interactions across cortical circuits as the medium for synchronous linking and binding among widely distributed brain areas. Comparing computational neural models with perceptual phenomena, Dehaene and Changeux emphasize the suddenness of the transition to conscious and reportable registration of stimulus events. Sergent and Dehaene (2004) and Del Cul et al. (2007) take their findings with the attentional blink test and backward masking, respectively, to be concordant with the notion of a discrete threshold for access to consciousness. Abruptness of onset of conscious experience is also an essential aspect of the extended psychophysical studies of Breitmeyer and Ogman (1984/2006).

A different (perhaps complementary?) point of view is represented by a group of investigators who attribute the distinction between unconscious and conscious vision to recurrent processing: Lamme and associates (Lamme and Roelfsema 2000; Super et al. 2001; Lamme 2006a, b) claim that reportable conscious visual experiences require that the "feedforward sweep" of neural activation from visual towards motor areas become extended to a "backward sweep" which consists of widespread recurrent activation of frontal, prefrontal and temporal cortex, putting "visual information into the context of the system's current needs, goals and full history" (Lamme 2003; Pascual-Leone and Wals 2001).

In addition to the foregoing considerations, it appears also required that the somatically embodied and environmentally reactive behavior be associated with adaptive autonomy and internal bioregulatory processes of emotional embodiment. Based on thoughtful analysis of extended clinical observations, Damasio (1994, 1999, 2001, 2003; Damasio et al. 2000), and more recently Rudrauf and Damasio (2006) view subjectivity and the experiencing "I" as essential aspect of Consciousness. It is a "feeling of knowing" that makes the relation to a perceived object salient to the organism. Feelings are grounded in the multidimensional, moment-to-moment shifting physiological internal body environment, associated with the subcortical regulatory structures of, for instance, Hypothalamus and Brain Stem Tegmentum, and the cortical formations of Insula and Cingulate regions. The act of a subject's conscious cognition is thought to consists of two mutually interdependent and interacting components: sensory events in transaction with the external world, and a 'feeling' which is the concurrent reading of the body's internal environment; the latter in some sense anchoring the subject's ownership of the former. This theory is consistent with a wealth of observations in Clinical Neurology, and with neuro-anatomical and neuro-physiological data (Craig 2002).

The foregoing brief overview is intended to underscore the two principal characteristics of the origin of events in consciousness: abruptness of onset, and the active engagement of substantial portions of brain; the latter supporting the basic idea of Baars ' Global Workspace Theory' of associating consciousness with widespread access among otherwise independent brain functions (Baars 1988, 2002).

The state space: concept and application

The rich source of recent observations with Brain Imaging, together with the long standing evidence on oscillatory brain activity from Electroencephalography and Coordination Dynamics contributed in the past two decades to the growing realization that the brain should be viewed as a complex dynamical system of unprecedented complexity (John 2002). This recommends adopting the state (phase) space approach for characterizing the brain's state as points (or circumscribed regions), and changing activity unfolding in time as trajectories in a high dimensional space. It is then also possible to conceive of behavior, cognitive functions and phenomenal experience similarly in terms of state space dynamics, and to examine corresponding trajectories in brain and mental spaces. Examples of this are: Wackermann's (1999) assessment of electroencephalographic field changes as state space trajectories, Hobson's (2000) view of different stages of wakefulness and sleep in terms of state space dynamics; the demonstration of global brain state transitions occurring simultaneously across multiple forebrain areas (Gervasoni et al. 2004; Fell's 2004) mappings between brain states and phenomenal experience, and Churchland's (1989, 2006) long standing explorations with comparing human phenomenological with neural-network activation spaces. As indicated in the Introduction, application of state space concepts in the form of Coordination Dynamics has significantly enriched the understanding of relations between global brain dynamics and behavior.

A state space as such is merely the repository of all potentially accessible states a system can assume. Each dimension of the state space corresponds to an independent system variable. System variables can also be considered as components of a state vector in state space. What makes thinking in terms of state space dynamics a powerful tool is the manner of progression in time of state vectors in state space, describing the trajectory of the system's evolution. Singularities (discontinuities) of the trajectories are associated with state space transitions at which point many conservative (equilibrium) physical systems can undergo a deep structural modification. It occurs when a certain system parameter reaches a 'critical' value. The study of these modifications is the subject of the (classical) Theory of Dynamic Critical Phenomena (Hohenberg and Halperin 1977; Stanley 1999). At the critical transition, the system presents qualitatively novel properties which warrant new descriptors and obey new physical laws: presenting, in fact, a new physical reality. The state transition of magnetization of ferromagnets is an illustrative example as is the familiar transition from water to ice.

How does this new physical reality come into being, and what does it entail? At the critical point of state transition, the system undergoes a profound reconfiguration which, among other features, is expressed as change of the correlation function of micro system elements. The correlation function characterizes how the value at one point in state space is correlated with the value at another point, reflecting the micro level's fine structure. While under stable conditions extending over short distances, correlation length progressively increases as the critical point of state transition is approached. At the critical point itself, correlation length diverges to the extent that only correlations extending over larger scales remain. This implies that the system, metaphorically speaking, looses a detailed 'memory' of its microscopic structure. Thus, the macroscopic manifestation is at the critical point essentially based on a kind of abstraction from the original micro level, with all but those micro level features preserved that now determine the novel macroscopic observables. This is also the point of drastic reduction of microscopic degrees of freedom. The change in correlations among the microscopic features at state transition can also be viewed as change to a coarser state space topology with new neighborhood relations among features, and thus associated with novel physical manifestations. Concurrently, the microscopic structure looses any characteristic length scale for system specific variables: it becomes scale invariant, i.e. fractal (Stanley 1999; Yeomans 1992/2002).

Recent observations of Chialvo et al. (2008) point to the relevance of these considerations for brain processes: applying the technique of Fox et al. (2005), voxel based correlations of BOLD activity of different brain regions were obtained in fMRI studies of humans (Baliki et al. 2008). These correlation maps were similar to those obtained computationally with Ising models in critical state transitions displaying long-range spin correlations. This observation supports the notion that long range correlations among neural groups may also obtain in the brain, as sign of it being in a critical state.

For complex systems far from equilibrium, most of the analytical and numerical methods of the 'classical'(equilibrium) theory remain useful, except for some restrictions: relaxing the balance condition of conservation and the absence of thermodynamic energy parameters. But lack of analytical solutions requires that in most instances numerical simulations must be used to identify a system's critical behavior. However, on the positive side, new possibilities arise in the form of state transitions to absorbing (i.e. irreversible) states, and to novel spatial structures which are influenced by the system's history (Hinrichsen 2006; Luebeck 2004; Odor 2004).

One of the amazing features of state transitions is that material systems of diverse physical properties at their microscopic level fall on state transitions in but a small number of classes with identical macroscopic properties, thus forming Universality classes; a corollary is the principle of multiple realizability, that is, a given system's macroscopic phenomenology may be shared by the microscopic states of many physically different systems. Universality and multiple realization designate that: (1) some details of the system which would figure in a detailed causal-mechanistic explanation of the system's behavior, are in the limit largely irrelevant for characterizing the macroscopic phenomenology of interest; and (2) different systems with vastly different "micro" details can exhibit identical behavior at the macroscopic level. The methods to elucidate both aspects are "coarse graining" (e.g., Schulman and Gaveau 2001) and the strategies of Renormalization Group Theory (Wilson 1979): the latter essentially, dimensionality reduction by successively coarse graining while maintaining self-similarity. Renormalization theory is a "general framework for extracting phenomenological relations among macroscopic observables from microscopic models that may not be precisely definable " (Goldenfeld et al. 1989). Thus, if what one is interested in is the macroscopic phenomenology, then the adoption of renormalization-like procedures and of asymptotic arguments is the path to follow.

Examples of notable universality classes of far-from-equilibrium systems are: Directed Percolation and the so-called voter universality class. Coupled map lattice models for spatiotemporal intermittency under an asymmetrical updating regime belong to the universality class of directed percolation (Rolf et al. 1998). Universal critical behavior is also reported for two-dimensional coupled map lattices (Kuznetsov 1992; Marcq et al. 1996; Just and Schmueser 2005). As a bridge to self-organization, absorbing state transitions in directed Percolation can occur with some systems under appropriate circumstances (Dickman et al. 1998).

As stated earlier, Topology and dynamics are inseparably linked in the constitution of networks and reflected by their universality class's defining scaling relation (Albert and Barabasi 2002; Dorogovtsev et al. 2000). One of the most intensely studied processes taking place on networks is Percolation (Stauffer and Aharony 1991/1994). Basically, a percolation process consists of the evolution of patterns in arrays of elements under a given dynamics. For reasons stated earlier, models of this kind on small-world networks are of particular interest (Newman and Watts 1999; Moore and Newman 2000; Newman et al. 2002). In computational models, the task consists in determining rules of transformation (i.e., a dynamics) that would generate certain types of patterns (e.g. so called Giant Components, i.e. certain patterns of connectivity within the network, as state transitions). It is then possible to determine computationally certain critical parameters, and compare with known Universality classes of physical matter.

Recent empirical findings and computational results suggest the neurobiological relevance of these considerations: 'avalanches' of neuronal activity occur spontaneously in superficial layers of cerebral cortex under a variety of experimental conditions; the power law distribution of avalanche sizes suggest that the tissue samples are in a dynamic state of criticality, possibly attributable to branching processes (Beggs and Plenz 2003, 2004; Haldeman and Beggs 2005); but other dynamic models such as phase transitions in percolation are conceivable (Plenz and Thiagarajan 2007). Percolation transitions were also described by Breskin et al. (2006) in cultures of brain tissue and acute cortical slices. Franovic and Milkovic (2007) determined that spike packet propagation in form of synfire chains (Gewaltig et al. 2001; Bienestock 1995) exhibit critical behavior corresponding to percolation phase transitions. Kozma et al. (2004, 2005) applied models of percolation to explore the dynamics of neuropil.

Discussion and conclusions

The aim of this essay is to assemble evidence suggestive for viewing the transition from neural processes of sensorimotor cognition to those associated with consciousness in the framework of critical brain state transitions. Brain states of reactive sensory-motor cognition and those associated with subjective awareness would differ as a result of a state transition which, in the framework of the Modern Critical Theory signifies fundamental differences in their respective physical realizations, not deducible from one another by continuous transformations. As a program of research (in the sense of Lakatos 1978) the foregoing framework would situate brains squarely into the domain of the Physics of Condensed Matter, as alternative to the conventional views of 'information flow' along neural relay stations, and related views (Werner 2007b).

This point of view places Cognitive Neuroscience into an entirely different framework of Scientific Reasoning which rests on the basic outlook in contemporary physics that one level of a system's organization can be viewed as coarse grained approximation of another level, each expressed on its own intrinsic scale. In this view, reality is composed of a hierarchy of scales: the intrinsic scale emerges at each level from that of the next finer scale by ignoring some of the (irrelevant) details of the latter (Laughlin 2005; Sokal and Bricmont 2004). In actual practice, the approach consists of delimiting the dominant from irrelevant parameters that shape the system's behavior, for the purposes of categorizing universality classes: i.e. classes of systems which approach asymptotically in the limit identical macroscopically observable behavior despite diversity at the microscopic level. As a corollary, what is of interest is the multiple realizability of emergent new macroscopic phenomena despite microscopic diversity (for details, see Batterman 2002). In this approach, the so called higher level description is not an approximation of the fundamental (low level) theory, but represents (qualitatively) new patterns of reality (Primas 1998). Most of the successful applications of this framework come from Thermodynamics and Statistical Mechanics near critical state transitions, but the principle can be illustrated as a generalization of Probability Theory: when sets of multiple independent population samples are subsumed under a Gaussian Distribution, then the parameters of the distribution characterize a (kind of) Universality Class (i.e. the ensemble), of which the individual sets of samples are independent realizations.

The foregoing sections applied this conceptual stance to the relation between brain states in four stages: (1) reviewing the evidence that the dynamics of the brain is poised towards critical stet transitions; (2) suggesting that critical state transitions may entail the principle of a "backward sweep" such as envisaged by Lamme and associated for the visual system, and/or involve the inclusion of interoceptive functionality in the active brain state; (3) that at certain 'tipping points' (Gladwell 2000), a brain state transition to a new qualitatively new configuration would occur; (4) that brain states before and after state transition differ in the respective scales of their description, with the post-transition state in the asymptotic limit being a coarse grained approximation of a universality class: a class at which microscopic details become largely inivisible, and where multiple realizability and different laws obtain. In this view, the neural structure of brains of adequate size belong to a Universality Class which can on state transition exhibit at a macro level a neural organization which can support the phenomenal attributes associated with consciousness.

The state space framework of micro- and macro levels implies inevitably an intersection of Complexity Science with the perennial philosophical problem of Emergence (Bedau 2002). Kim (1999) identified five main tenets of "the doctrine of Emergentism", singling out as defining features the coming-together of lower-level entities in new structural configurations; the origin of "higher level" properties, their unpredictability and irreducibility and, finally, the causal efficacy of emergent properties of their own. Bedau (2002) distinguishes strong and weak emergence: the former having irreducible causal powers—a dramatic form of ontological novelty—the latter being consistent with and functioning via micro level laws. However, in light of the foregoing discussion of the singular nature of the limiting asymptotic relation between the finer and the coarser level, it appears that the singular limits are in fact the interface where new objects, properties and laws originate. Taking the view of reality as a hierarchy of scales as basis, objects and properties in reality appear at each level in the hierarchy with their own organizational laws and structure, and with the propensity to undergo sharp state transitions (Laughlin 2005). States are cases of emergence, based on levels of organization in Nature having walls of scales: a set of rules can operate at one level and, yet, be largely invisible (and, thus, irrelevant) at another.

What, if anything, can be learned from applying this line of thought to the neurology of Cognition and Consciousness? The intent all along was to adduce plausibility to viewing the neurology of episodes in consciousness as global brain state space transitions: the emergence, under certain circumstances, of a new organizational structure with novel qualitative phenomenology, distinct from the level of the neurology of cognition. At the latter level, the state transition would consist of including additional neuronal centers in the zone of active neural processing (see e.g., Baars et al. 2003), or redirecting the processing flow (Lamme 2006b). Could such 'backward flow' be comparable to the activation of V1 in the imagination of visual scenes (Kosslyn et al. 1997, 2001; Ganis et al. 2004; Mechelli et al. 2004)?; and could such configuration changes be considered as a kind of 'downward causation'?

The general outline of this proposal entails practical consequences for the conduct of research: in the first place, to seek evidence in the temporal evolution of magnetoencephalographic signals from human brain that could reflect the accretion of Giant Components, especially those which would also encompass brain regions which signal interoceptive physiological conditions of the body. An illustrative example of the type of study design that may be informative is provided by the work of Braeutigam et al. (2001, 2004) on identifying stages in real life decision processes. Deahaene et al. (2006) list several methodological refinements which would also yield illuminating insights.

The second consequence follows, in principle, the recommendation of Atkinson et al. (2000) to investigate (loosely stated) 'computational correlates of consciousness'. Numerous specific questions arise the answers to which are beyond one's intuitive grasp: take for instance the observations of Basset, Achard, Salvador and other investigators cited earlier, indicating the presence of multiple functional small-world networks, each carrying oscillatory activity of different frequencies. What is the space of potential dynamic evolutions such a highly differentiated system can undergo? What are their "tipping points" (Gladwell 2000) for state space transitions and Giant Component formation? What is the space of potential reconfigurations that such a systems can undergo under perturbation? How could reversal of activity flow in networks come about? Under what conditions sustain such systems stability? What forms of interactions may obtain among networks conveying different oscillatory frequencies? What if different active networks share some nodes? Being poised towards instability, how would state transition in one network affect others? Or are the frequency-specific networks functionally segregated to the extent that one may view them as chords in a string instrument? Surely, to come to appreciate the space of possibilities in brain dynamics, these kinds of questions need exploring in their own right. In addition, one may also expect that simulations probing these kinds of questions will provide useful pointers for interpreting imaging data and, perhaps, also raise probing questions for empirical analysis.

Whatever the specific question under study, it amounts in the interpretive framework of this essay to exploring the space of brain-like non-equilibrium dynamical systems on lattices, identify universality classes, and establish the conditions for state space transitions. This approach is guided by the ground rules of Renormalization and asymptotic arguments in the study of the phenomenology of macrostates of complex dynamic systems, where microscopic details become to some extent invisible and/or irrelevant.

Bear in mind that the main thrust of this essay is the notion of emergence of new patterns of reality in the evolution of complex hierarchical multilevel dynamic systems that cannot be deduced from their lower level configurations, but can, at best, be approximated by equivalence classes of microscopic models. It is then a pragmatic issue to select from among candidate models those with best predictive value for macrosystem performance, and in closest accord with features and constraints imposed by the system's known micro- and mesoscopic organization.

Summary

The relation between neural processes thought to be associated with cognition and consciousness is discussed in terms of the theory and concepts of Critical State Transitions. Cognition and consciousness are viewed as a lower and a higher level, respectively, in the brain's multilevel hierarchic neural organization. Empirically established landmarks of brain dynamics, network configurations and their role for conveying oscillatory activity of certain frequencies bands are reviewed to propose that the relation between neural processes of sensory-motor cognition and those of events in consciousness are of the same category as is characterized by state transitions in non-equilibrium physical systems. The heuristic merits and approaches for empirical validation of this view by suitably designed brain imaging studies, and for computational simulations of the proposed principle are discussed.

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