Oscillations, metastability and phase transitions in brain and models of cognition

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Abstract

Neuroscience is being practiced in many different forms and at many different organizational levels of the Nervous System. Which of these levels and associated conceptual frameworks is most informative for elucidating the association of neural processes with processes of Cognition is an empirical question and subject to pragmatic validation. In this essay, I select the framework of Dynamic System Theory. Several investigators have applied in recent years tools and concepts of this theory to interpretation of observational data, and for designing neuronal models of cognitive functions. I will first trace the essentials of conceptual development and hypotheses separately for discerning observational tests and criteria for functional realism and conceptual plausibility of the alternatives they offer. I will then show that the interpretation of phase transitions in brain activity, and some of its models, in terms of statistical mechanics provides a new and possibly revealing perspective on brain events in cognition.

1. Introduction

The application of the Dynamical System framework in Neuroscience since the mid 1980's has notable precursors: Ashby (1952/1960) suggested that brain phenomena might best be understood in terms of dynamic system models. Katchalsky's et al (1974) stated that .."waves, oscillations, macrostates emerging out of cooperative processes, sudden transitions, patterning, etc seem made to order to assist in the understanding of integrative processes of the nervous system that remain unexplained in contemporary neurophysiolog". Haken (1983) proposed to view the brain as a self-organizing pattern forming system that operates close to instability points which allow flexible switching between coherent states; and Freeman's (1975, 2000) studies of wave patterns and their dynamic principles have yielded numerous findings and conceptual elaborations of relevance for Cognition and Consciousness

Recent investigations have generated several dynamical hypotheses of brain processes which form a kind of "family resemblance", though also differing in some important aspects and –where applicable- in their respective computational models. For clarity of exposition, I will trace the various strands of conceptual development and hypotheses separately, notwithstanding the many cross links among them. While on guard for superficial analogies turning on close scrutiny into (possibly) decisive differences, the focus will be on identifying the features they share, and for analyzing differences; the latter for discerning observational tests or conceptual criteria for the plausibility of the alternatives they offer. I will assume these hypotheses to aim at explicating processes of conscious access understood as reportability of subjective experiences (Dehaene and Changeux, 2004).

2: Background: Data and Models

2.1: Oscillatory activity and Coordination Dynamics

I take the remarkable discovery of stimulus induced oscillatory and synchronous neuronal activity with the predominant frequency in the 40 Hz range (gamma wave activity) as starting point. In sensory systems, the

phase synchronization of oscillation links neurons functionally together to groups that respond to identical stimulus features (Gray and Singer, 1987,1989; Eckhorn et al. 1988). The functional neuron assemblies thus formed consist of elements which are distributed in space, but are 'locked' together by a common signal phase. The possibility of this synchronous activity of neuronal assemblies being a candidate for linking separate stimulus features to objects of conscious perception was intensively investigated (Engel et al. 1999, Lamme et al. 2000; Lutz et al. 2002; Ribary et al. 1991, Singer et al. 1997; Tallon-Baudry and Bertrand, 1999). However, here, I will direct attention to the two unusual properties of this oscillatory activity as of principled significance for brain theory: first, virtual simultaneity and very short onset latency in the oscillating ensemble, implying a process on a faster time scale than conduction and synaptic delays would permit (Singer, 1998; Roelfsema et al. 1997); and second, their pattern of short oscillatory sequences interrupted by epocs of stochastic activity (Murthy and Fetz, 1992).

Simulation studies of neural assemblies characterized the switching between synchronous and stochastic activity as a phase transitions , attributable to synaptic nonlinearity and fluctuations from peripheral input and/or interaction with other assemblies (Bauer and Pawelzik, 1993). This justifies subsuming the cortical oscillatory activity under the category of Kuramoto's (1984) "self-synchronization transitions" as a paradigm for synchronization phenomena and a mode of self-organization in populations of interacting elements (Acebron et al. 2005). The revealing aspect of the oscillatory neural activity under discussion is the already mentioned short onset latency: phase transitions in nonlinear dynamic systems occur with very short latency as one of their universal properties and signatures. This classifies the neuronal ensembles generating oscillations in the 40 Hz range as self-organizing nonlinear systems.

Activity in a wider frequency band than gamma oscillations reveals an intricate dynamics of surprisingly long lasting activity patterns of appreciable spatial extent, initiated by a sensory event or in task situations. The time course of signal distribution across the multiple cortical areas of the visual system extends over some 150 msec from time of onset of stimulus, with the sequence of activation departing drastically from what one would expect if the cortical regions were activated sequentially in a pure hierarchy: for example, local field potentials (LFP) in Visual area V4 have a much longer latency than, for instance, the temporal areas, although geographically much closer to the cortical visual input are V1 (Schmolensky et al. 1998). A meta-analysis of visual response latencies in the macaque cerebral cortex ascertained a complex pattern of feed-forward and recurrent activity flow: for several hundred msec after a brief stimulus, the temporal sequence of activation departs from the topological proximity of activated structures (Lamme and Roelfsema, 2000). A complicated dynamics of activation and deactivation of cortical regions is also generally associated with the execution of attention-demanding tasks, with some regions being activated while others recede to relative quiescence. This task-related regional dichotomy of activity is also demonstrable in the resting state, suggesting a cortical network of intrinsically anticorrelated components (Fox et al. 2005). In perceptual tasks, synchronous local field potentials (LFP) oscillating at frequencies from 12 to about 80 Hz signal sequential patterns of co-activation of different brain regions, extending up to 500 msec in successful (but not failed) discrimination performance (Bressler, 1995; Ding et al. 2000; Bressler andKelso, 2001; Rodriguez et al. 1999) with different neuronal assemblies evolving in different frequency ranges (von Stein and Sarntheim, 2000). Finally, brain imaging during natural viewing conditions reveal the temporal organization ("chronoarchitecture") of brain activity since functionally different brain regions exhibit individually distinct temporal activity patterns (Bartels and Zeki, 2004).

The conceptual and methodological implications of these and related findings are consonant with the principles of Coordination Dynamics (CD) of complex systems. This is a framework for studying the manner in which interdependencies among a system's components dynamically evolve in time. In the application of this approach to the brain, the phase relationship of LFP's is taken as the significant control parameter (collective variable) for ordering the sequence of activation patterns in time and space (Varela et al. 2001; Bressler and Kelso, 2001). Unlike the msec and mm range of local coordination, times extend up to several hundred msec, and spatial interdependence may encompass diverse cortical and subcortical zones, and the brain stem. High

speed Elecroencephalography and Magneto-Encephalography supplied data for a refined analysis of relationships between brain activity and perceptual-cognitive behavior. A review by Bressler and Kelso (2001) summarizes the essential results of numerous studies which show that both behavior and brain activity undergo a sudden transition from one stable state to another at some critical stimulus parameter. This phenomenon is thought to attribute to the brain the universal property of complex systems operating in a metastable dynamics. This may be due to an interplay between integrating and segregating tendencies (see also below) or attributable to dynamic instabilities in complex attractor manifolds Friston (2000). Evidence for the brain's metastability is also evident in a recent study of Freeman & Holmes (2005), based on the analysis of spatio-temporal patterns in the 12-80 Hz band of the Electroencephalogram.

2.2: The Dynamic Core Hypothesis (DCH)

Plasticity of synapses and neuron connections afford a causal link between the functional organization of neuron assemblies and the world, adaptive to use and disuse. The Theory of Neuronal Group Selection (TNGS), also referred to as the Darwinian Brain, is an application of this principle (Changeux, 1983; Edelman, 1987,1989, 1993; Tononi and Edelman, 2000]. A primary repertoire of anatomical connections established during development responds to experiential exposure to the environment with differential amplification of synaptic populations. The second central notion is reentrant mapping: this is a dynamic process that is inherently parallel and distributed. It consists of ongoing signaling between separate neuronal groups in a reciprocal and recursive fashion over cortico-cortical, cortico-thalamic and thalamo-cortical radiations. Neuronal group selection and reentrant mapping, together, are considered the prerequisite for establishing new and sustaining existing statistical signal correlations between groups of neurons. Neuronal groups thereby come to reflect spatiotemporal properties of signals arising in the environment, and serviceable for perceptual categorization.

Generalization of this principle to cross-modal perceptual categorization is accomplished by dynamic structures that encompass multiple reentrant local maps (sensory and motor) and interaction with basal ganglia, brain stem and cerebellum; the latter for perception-action coupling. Within such global mappings, long-term changes in synaptic strength favor the formation of neuron groups with correlated activity as basis for memory. Memory in global mappings is procedural, and requires dynamical re-assembly by rehearsal. Note that each re-assembly of a global memory may be constituted by different neuron populations: a consequence of the degeneracy (redundancy) of neuronal groups.

Reentry is instrumental for generating oscillations in the simulated models: Sporns et al. (1991) and Tononi et al. (1992)] established in their respective models the linking of stimulus features by reentrant circuitry, within and between segregated cortical areas. It depends in these studies on the occurrence of rapid changes in efficacy of reentrant connections, and is an aspect of segregation and integration of elementary features into objects and background through temporal correlation and phase relationships among neuronal groups. In a very large computer model of 65,000 spiking neurons, topographically organized into a primary and secondary visual cortical area and two associated thalamic regions, synchronous oscillations emerged spontaneously, even though the networks was not designed to produce any form of specific dynamics (Lumer et al. 1997)

Conscious experience is in this theory associated with global properties of large but distinct sets of distributed neuronal groups: the Dynamic Core (DC). The theory associates cognitive events with the formation of distributed clusters of neurons that are intensely interacting with each other (i.e.: integrated) and, at the same time, are quite distinct and differentiated from the rest of the system. The neuron clusters of DC achieve high integration within hundreds of msec through reentrant interactions in the thalamo-cortical system. DC must be viewed as a process, creating transiently the clusters of DC, which reflect rapidly shifting functional connectivity among distributed groups of neurons, rather than being constrained by anatomical proximity.

For the interplay between the two seemingly opposing tendencies of differentiation and integration, Tononi et al (1994) defined a statistical measure which defines the amount of 'structure' within a system's dynamics, as expression of its "complexity" : its value is high for systems with subsets of large mutual statistical dependencies. In such systems, different parts can engage in separate activity and yet remain interdependent (Ton oni and Edelman, 1998). They are also candidates for metastability (Sporns, 2004). Functional segregation is epitomized by stimulus feature detectors in cortical receiving areas; functional integration is expressed in temporal correlations and synchrony in the large-scale, reciprocally interconnected cortical network and thalamic regions. The central role attributed in this theory to processes of integration and differentiation in neuronal groups directed attention to whether (and if so, in what manner) neuronal networks are equipped to support these processes. In a remarkable convergence of results from Computational Neuroanantomy (Sporns and Koetter, 2004), the statistical mechanics of networks (Albert and Barabasi, 2002) and computer simulations (Sporns et al, 2000; 2004) ascertained that the particular form of clustered organization encountered in biological (natural) cortical networks would indeed be supportive of synchronous processing and efficient signal exchange, and superior to other network topologies (for review: Sporns, 2004). and references cited therein).

2.3: Global workspace models

2.3.1: Baars' Global workspace model

Partly in distinction from and partly overlapping with extant psychological theories of conscious experience, Baars (1988) introduced and later extended (1997) a "Cognitive theory of Consciousness". The theory postulates a multitude of relatively small special-purpose processes, almost always unconscious. Coalitions of such processes gain access to a limited capacity global workspace which serves to integrate competing and cooperating input networks and is the gateway to consciousness. Messages from this global workspace are broadcast to all the unconscious processors to recruit their participation for dealing with novel situations or solving the current problem. All this occurs under the auspices of certain contexts, each being itself a coalition of processes, jointly constraining conscious events.

In the original book of 1988 and in numerous subsequent publications, Baars illustrated that the three main construct of the theory (namely Global workspace, unconscious special processors and contexts) and their interaction pattern can be construed to be sufficient for most (possibly all) aspects of Cognition and Consciousness. His original approach was informal, descriptive and primarily appealing to psychological intuition. Nonetheless, in a review published in 2002, Baars (2002) could cite a large number of investigators implicating one form or another of a 'global workspace' in cognition and consciousness, however not necessarily embracing Baar's tripartite model. The rallying point appears to be the notion that some form of "global workspace" is required for widespread interaction between otherwise independent brain functions: the idea of a 'global workspace' had entered the discourse of consciousness studies, albeit in a variety of shades of meaning.

In subsequent publications, functional interpretations in neurophysiological terms were introduced by Baars and associates in a 'neural global workspace' (Newman and Baars 1993), primarily in relation to attention in schemas of neural network models (Newman et al. 1997), and similar to those which Taylor and Alavi (1993) had applied earlier. Franklin and Graesser (1999) and Franklin (2003) took a different approach: they implemented the global workspace concept in several successive generations of software agent models in the tradition of Artificial Intelligence. None of these efforts addresses the dynamics of processing in the global workspace and are, therefore, outside the scope of this essay.

2.3.2: Wallace's dynamic global workspace hypothesis

In a series of recent publications Wallace (2005a) supplied a dynamics to a Global Workspace. Here I will offer an intuitive account of the formally developed perspective taken in Wallace (2005 b) which applies information theoretic considerations and draws on resources from theories of network structure and dynamics (Erdos and Renyi, 1960; Newman, 2003).

To begin with, a loosely connected network of unconscious modules is considered, corresponding essentially to the unconscious processors of Baars' theory. Next, the relation among them is characterized in terms of their mutual information. Non-zero mutual information among modules can formally be considered as linkages among them which constitute fleetingly a (functional) Global Network. Network theory now specifies conditions under which sub-networks can become transiently formed. One of them can encompass the majority of the network's nodes, forming in network jargon a 'Giant Component'. In terms of network dynamics, this can be considered a phase transition. The formation of the 'Giant Component' is considered to reflect a collective cognitive phenomenon. One can readily imagine the complex dynamics of this model: a continuous flux of mutual information among the special purpose processors, at each point giving rise to a fleeting network which, at certain critical points, coalesces momentarily to a Giant Component, only to be restructured by new states of the information processors.

This sketch of the model is merely intended to convey an intuitive "feel" of the model's dynamics and fails to do justice to its formal sophistication and to the numerous details in its application to, for instance, Generalized inattentional blindness and mental disorders Wallace (Wallace, 2005 c; 2006)

2.3.3: The Global Neuronal Workspace hypothesis (GNWH)

The Global Neuronal Workspace hypothesis was described in details by Changeux & Dehaene (1989) and Deahaene & Naccache (2001) and most recently summarized by Dehaene & Changeux (2004). It relates to Baar's cognitive theory of consciousness, but is distinguished from it by its particular and detailed functional organization, and its implementations in dynamic computational models.

The hypothesis postulates two computational spaces of distinct patterns of connectivity: 1) a collection of subcortical, automatic processors, each specialized for a particular signal input which is provided via encapsulated local and medium-length connections; and 2) a global neuronal workspace with the capacity for wide-spread, long-range connections for reentrant signal flow between it and the specialized processors. The workspace is a dynamic concept: workspace neurons are not sharply delineated anatomically, but distributed among distant association areas (Dehaene and Changeux, 1997, 2005; Deahaene et al. 1998). The decisive event is the activation of GNW: its onset is sudden, consists of coherent synchronized neuron activity in multiple distant cortical areas, mobilizes additional peripheral processors, and is sustained for several hundred msec by reentrant, self-amplifying thalamocortical signal flow. Between episodes of activation, the neurons of GNW are in a metastable state of permanent spontaneous activity which is sustained by ascending neuromodulatory input. When of sufficient intensity, the network will display gamma oscillations of thalamo-cortical origin and possibly sudden surges of activation which may be identified with 'vigilance' (Llinas et al, 1998) : they enhance the activation of GNW by sensory stimuli. Activation of GNW also occurs with intense sensory stimulation in the absence of facilitation. The GNW activation is considered a phase transition in the metastable dynamics of the brain. This implies that only one single global representation can be sustained at any one time. In the model described below, it persists for 200-300 msec. GNWH postulates that global activation of a GNW is associated with reportability of a subjective experience (Deahaene and Changeux, 2004).

The basic design of GNW was implemented in several Neural Network models, with McCulloch Pitts as computational elements, and proved satisfactory for emulating aspects of human performance in a variety of (effortful) psychological-behavioral tasks (Deahaene et al. 1987,1998). To convey the operational flavor of the

theory, I will focus on the most recent model by Dehaene et al. (2003) of a network of single compartment model neurons with explicitly specified ionic conductances and synaptic currents for simulating features of the cortical inter- and intra-columnar connectivity and as cortico-cortical projections. The target of the model was a modified attentional blink paradigm for which conditions for reportability of presence or absence of stimuli were determined in human trials: subjects saw serial visual presentation of distractors, interspersed with two targets T1 and T2; the task was to rate T2 visibility and then to report T1 identity. Typically, reportability of T2 drops at for several hundred msec after T1 presentation.

For the simulation of the human task, the model was placed in a regime of spontaneous thalamo-cortical oscillations. The attentional blink test was simulated by stimulating two groups of thalamic neurons, one coding for T1, the other for T2. The index of model performance was the degree and extent of activity across the cortico-thalamic hierarchy. As to be expected, network activation evoked by T1 stimulation set a long-lasting dynamic brain-state in motion. But the activation elicited by T2 stimulation dependent tightly on its timing: T1 elicited activity prevented T2 activation from propagating to higher cortical levels and abolished part of the top-down amplification in reentrant circuitry, with the global network seemingly acting as a bottleneck (Sigman and Deahaene, 2005). Selective lesions of the long distance connections in the model corrupt the model performance.

3: Discussion

3.1: Oscillations and metastability

The models and hypotheses under discussion are predicated on the assumption of the unity of consciousness which the computational models aim at substantiating. This foundational assumption is, however, not uncontested. At least for color and visual motion, Zeki (2003) advocates that consciousness for these attributes occurs at distinct processing sites which also subserve perception. An additional argument for disunity is the asynchrony and temporal hierarchy of 'microconsciouness' of separate visual stimulus attributes, most recently proclaimed as a chronoarchitectural principle (Bartels and Zeki, 2004).

A recurrent theme of brain related models and hypothesis is the role of oscillations as mechanism for communication among neural elements. Van der Malsburg (1981/1994) spoke of this long ago as the Correlation theory of brain function. How does synchronization in neural ensembles come about ? Two mechanisms are generally invoked (Pikovsky et al. 2001): one, entrainment of oscillators triggered by an external force; the other, entrainment by a pulse (or pulse train) for re-setting of phase. In the latter case, the coordination of synchrony over an ensemble of elements usually unfolds in stages: beginning with a few oscillators becoming synchronized, a mean field forms that drives other oscillators. Note the circular causality: oscillators initially setting up a mean field recruiting other oscillators which, in turn, contribute to the mean field. This is the "enslaving principle" of Haken (2002).

Oscillatory activity is pervasive and virtually ubiquitous in physiological and biochemical processes, as it is also generally recognized an engineering principle: signal encoding in frequencies affords resistance to degradation by noise and enhances precision of control (Rapp,1986). The point to be noted is simply that recourse to oscillatory functions is a tool that Nature applies virtually across the board when precision and process control in an assembly of components is required for their work on "world making". They are generally understood as "binding" neuronal elements to functional units of higher order, i.e. assemblies for perceptual or motor tasks.

DCH and GNWH attribute an essential function to reentrant, repetitive activation of some neuronal dynamic core assembly which bears some resemblance with the workspace in Baar's system. Here I will focus on the notion of workspace in DCH and GNWH: although differing in essentials (to be discussed below), it is a fleetingly constructed assembly of distributed neurons which is required to persist for a time span in the several hundred msec range for entering into consciousness: In GNWH, occurrence of conscious states would be a

sudden transition in brain space activity which Sergent & Dehaene (2004) likened to the 'catastrophes' in Thom's (1983) system of structural stability and morphogenesis. Instability of network responsiveness is also encountered with the stochastic fluctuations of spontaneous neural activity, and is an aspect of the formation of 'Giant Components' in Wallace's Hypothesis. Coordination Dynamics also speaks in terms of several hundred msec when describing the task related cortical wave patterns.

The dynamical structural motifs of integration and differentiation considered essential in DCH are also of functional significance in Coordination Dynamics (Bressler and Kelso, 2001). They predispose for metastability in all cases. Integration and differentiation in neural organization are essential operational principles in DCH, but not specific requirements in GNWH. Hence, demonstration of their existence could in principle be a distinguishing criterion, but the practicality of this is open to question. Related but even more pressing: is the dynamic core physically demonstrable at all ? It would require demonstrating the rapid and flexible clustering among distributed neuronal groups, persisting for a few hundred msec before shifting to another pattern. Does the composition of the dynamic core change with changing cognitive tasks ? The answer to these questions awaits new approaches in imaging techniques, but identifies possible criteria. However, electroencephalographic and fMRI data reveal transient binding of disparate brain regions through synchronized oscillations (Koenig et al. 2005;] and Lehman et al (1998) describe brain electric microstates as momentary building blocks of conscious activity, persisting for some 100 msec.

Inventing brains in computational models and observing them with the tools of Coordination Dynamics converges to the issue of timing: several hundred msec are required for constituting and sustaining the dynamic core and the global workspace in their respective hypotheses; observed brain events in Coordination Dynamics also occupy durations of this order of magnitude. Recall that it takes some 500 msec in human subjects for a stimulus to the somatic sensory cortex to become experienced, referenced to the short latency component of the Cortical Evoked Potential (Libet, 2004). With respect to the time course, the microgenetic approach in perception offers a suggestive parallel: it is based on the idea of a 'gradual maturing' of the subjective perceptual experience in the sequence of different components of the cortical evoked potentials, ranging from the fast positive component at 20-60 msec to the negative component at 100-150 msec and the positive deflection at 300 msec (Bakhman, 2000). This would attribute to the reentrant activity the function of constructing the contents of the conscious state which culminates in the phase transition to a new cortical state. If there is any merit to this suggestion, it would have significant consequences for the experimenter: rather than seeking a correspondence between subjective report or behavior with a punctate (in space and time) measurement in fMRI , genuinely informative neural data would be obtained from following trajectories of phase space evolution in brain space and time (Werner, 2005).

Here I propose a conceivable experimental design for addressing this issue: obtain fMRI records sequentially after stimulation, track the flow of brain states in phase space, look for sudden transitions and singularities, and relate their timing to behavior manifestations or verbal reports. Simultaneity of a subjective experiential verbal report and a singularity in the fMRI phase space evolution would be supportive evidence for Coordination Dynamics and global workspace models, each in its own way focusing what really seems to matters in the natural brains: the evolution of state space representations to critical points of transition to qualitatively new and different states.

3.2 : Phase Space Dynamics

A recurrent theme in the foregoing sections was to consider the brain as a complex dynamical system, operating in a metastable regime, as balance between differentiating and integrating tendencies. Within this system and under certain conditions, distributed sets of neurons can transiently assemble to functional clusters: be that as a source of oscillations in CD, as the dynamic core in DCH, as the 'Giant Network', or as the global neuronal workspace in GNWH. Albeit with some differences, the three hypotheses CD, DCH and GNWH

attribute essential functional significance to the transient activation of some clusters of neurons. For Dehaene and Changeux (2004; 2005) these functional clusters are exquisitely poised towards bifurcation and phase transitions: their expression 'ignition' is particularly apt to convey the suddenness and the extent of spread of activity in the GNW.

In Nature, phase space dynamics is a physical process that runs its course under the influence of forces intrinsic to the system, and that may impinge in the system from its environment. Mahner and Bunge (1997) consider phase space an ontological fundamental in Biophilosophy. In this and other like situations, one needs to face the question whether a given system is intrinsically dynamical, or whether it is merely the case that it can be understood, interpreted, and simulated as dynamical system. Reassuring evidence for intrinsic brain dynamics comes from observations of dynamical switching of cortical (Kenet et al. 2003), and from the dynamics of the brain's ongoing baseline activity (Gusnard and Raichle, 2001). Supporting evidence is also obtained from the application of fMRI in human subjects to identify functional cortical networks: in a perceptual-motor task. the frequency distribution of distances between network nodes characterizes the nets as scale-free (Eguiluz et al. 2005). This corroborates the cortical network structure referred to earlier which was derived from computational Neuroanatomy and computer simulations, and is a signature for critical dynamics (Bak, 1996; Chialvo, 2004).

In statistical mechanics, phase transitions occur when a given state of the system becomes unstable and is replaced by a different dynamics at the microscopic (component) level. The transition occurs when one of the system's control parameter reaches a critical value: this is exemplified in GNWH as the crescendo of the self-amplifying recurrent activity. A new microstate is typically associated with reduction in dimensionality, destruction of symmetries in space and time, and the creation of qualitatively novel attributes at the microlevel and associated new phenomenological macrostate descriptors (Le van Quyen, 2003). Phase transitions in Nature have generally tangible consequences and are not merely creations of computational models: think, for instance, of water freezing to ice, and the underlying quantitative and qualitative changes of micro- and macroscopic descriptors. Accordingly, we need to ask: what becomes of neural ensembles in phase transitions to Global Neuronal Workspaces ? How is the qualitative novelty expressed in this case ? At a first glance, we may assume reduction of dimensionality of the (transiently) integrated global neuronal workspace. In addition, the integration of activity within the neural workspace will presumably by new patterns of correlations among neuronal elements. May there still be other aspects of novelty, not yet identified : for instance changes of scales of space and time, and scale invariance? What symmetries are broken, which are retained ? What new pattern of flow in phase space ?

Once committed to Phase Transitions, statistical mechanics opens the resources of Universality classes (Yeomans, 2002) that may suggest additional, not yet thought of properties of GNW. It is pursuing these kinds of questions which seem essential for coming to understand the functional organization of those transient formations of the brain that – according to the theory - do (or are) the cognizing. The question for Cognitive Neuroscience then turns to: what precisely are the statistical mechanical properties of these transient brain states, and how to gain insight into their distinctive features ? Recourse to simulation studies of phase transitions in two- or three dimensional lattices may be able to aid one's intuition. As an example: the recent work of Kozma et al (2004) offers valuable pointers to the conditions of critical behavior and scaling properties with potential for phase transitions in cellular structures. Generalizing from simulation studies of this kind to phase transitions in brain structures may be the way to come to appreciate the role which their genuinely novel features at micro- and macrolevels may fulfill in cognition.

References:

Acebron JA, Bonilla LL, Perez CJ, Ritort F, Spigler R (2005) The Kuramoto model: a simple paradigm for synchronization phenomena. Rev Mod Phys 77:137-185.

Albert R, Barabasi AL (2002) Statistical mechanics of complex networks. Rev Mod Phys 74:47-97.

Anderson PW (1972) More is different. Science 177:393-396.

Ashby R (1960) Design for a brain. Chapman & Hall, London.

Baars BJ (1988) A cognitive theory of consciousness. Cambridge University Press, Cambridge, 424 p.

Baars BJ (1997) In the theater of consciousness. Oxford University Press, New York. 193 p.

Baars BJ (2002) The conscious access theory: origins and recent evidence. Trends Cogn Sci 6:47-52.

Bakhman T (2000) Microgenetic approach to the conscious Mind. John Benjamins Publishing Company, Amsterdam. 298 p.

Bak P (1996) How Nature works: the science of self-organized criticality. Copernicus, New York. 212 p.

Bartels A, Zeki S (2004) The chronoarchitecture of human brain – natural viewing conditions reveal a time-based anatomy of the brain. NeuroImage 22:419-433.

Batterman R.W. (2002) The devil in the details: asymptotic reasoning in explanation, reduction and emergence. Oxford University Press, Oxford. 144 p.

Bauer HU, Pawelzik K (1993) Alternating oscillatory and stochastic dynamics in a model for a neuronal assembly. Physica D 69:380-393.

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

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

Changeux J-P (1983) L'homme neuronal. Fayard, Paris, 419 p.

Changeux J-P, Dehaene S (1989) Neuronal models of cognitive functions. Cognition 33:63-109.

Chialvo, DR (2004) Critical brain networks. Physica A 340:756-765.

Dehaene S, Naccache L (2001) Towards a cognitive neuroscience of consciousness: basic evidence and a workspace framework. Cognition 79: 1-37.

Dehaen S, Changeux J-P, Nadal J-P (1987), Neural networks that learn temporal sequences by selection. Proc Nat Acad Sci USA 84:2727-2731.

Deahaene S, Changeux J-P (1997) A hierarchical neuronal network for planning behavior. Proc Natl Acad Sci USA 94:13293-13298.

Dehaene, S, Kerszberg M, Changeux J-P (1998) A neuronal model of a global workspace in effortful cognitive tasks. Proc Natl Acad Sci USA 95:14529-14534.

Dehaene S, Sergent C, Changeux,J-P (2003) A neuronal network model linking subjective reports and objective physiological data during conscious perception. Proc Natl Acad Sci USA 100:8520-8525.

Deahaene S, Changeux J-P (2004) Neuronal mechanisms for access to consciousness. In M Gazzaniga ed. The Cognitive Neurosciences , 3rd edit, Norton, N.Y., pp.1145-1157.

Dehaene S, Changeux J-P (2005) Ongoing spontaneous activity controls access to consciousness: a neuronal model for inattentional blindness. PLoS 3(5), e141.

Ding M, Bressler ST, Yang W, Liang H (2000) Short-window spectral analysis of cortical event-related potentials by adaptive multivariate autoregressive modeling: data processing, model validation, and variability assessment. Biol Cybern 83:35-45.

Eckhorn R, Bauer R, Jordan W, Broisch M, Kruse W, Munk M, Reitboeck HJ (1988) Coherent oscillations: a mechanism for feature linking in the visual cortex. Biol Cybern 60:121-130.

Edelman GM (1987) Neural Darwinism: the theory of neural group selection. Basic Books, NY. 371 p.

Edelman GM (1989) The remembered present: a biological theory of consciousness. Basic Books, NY. 346 p.

Edelman GM (1993) Neural Darwinism: selection and reentrant signaling in higher brain function, Neuron 10:115-125.

Edelman GM, Tononi G (2001) Consciousness: how matter becomes Imagination. Penguin, London. 274 p.

Eguikluz VM, Chialvo DR, Cecchi G, Baliki M, Apkarian AV (2005) Scale-free Brain functional networks. Phys Rev Lett 94:018102-1.

Engel AK, Fries P, Koenig P, Brecht M, Singer W (1999) Temporal binding, Binocular Rivalry, and Consciousness. Consciousness and Cognition 8:128-151.

Erdos P, Renyi A (1960) Publications of the Mathematical Institute of the Hungarian Academy of Sciences 5:17-61.

Franklin S, Graesser A (1999) A software agent model of consciousness. Consciousness and Cognition 8:285-301.

Franklin S (2003) IDA: a conscious artifact ? J.Consciousness Studies 10:47-66.

Freeman WJ (1975) Mass action in the nervous system. Academic Press NY.

Freeman WJ (2000) Neurodynamics. Springer, New York

Freeman WJ, Holmes MD (2005) Metastability, instability, and state transitions in neocortex. Neural Networks 18:497-504.

Fox MD, Snyder AZ, Vincent JL, Corbetta M, van Essen DC, Raichle ME (2005) The human brain is intrinsically organized into dynamic, anticorrelated functional networks. Proc Natl Acad Sci USA 102:9673-9678.

Friston KJ (2000) The labile brain I. Proc R Soc Lond B Bio 355:215-236.

Gray CM, Singer W (1987) Neurosci.Abst. 404:3.

Gray CM, Koenig P, Engel AK, Singer W (1989) Oscillatory responses in cat visual cortex exhibit intercolumnar synchronization which reflects global stimulus properties. Nature 338:334-337.

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

Gusnard DA, Raichle ME (2001) Searching for a baseline: functional imaging and the resting human brain. Nat Rev Neurosci 2:685-694,

Haken H (1983) Introduction. In E Basar, H Flohr, H,Haken ed. Synergetics of the brain. Springer Berlin.

Haken H (2002) Brain dynamics. Springer, NY. 245 p.

Katachalsy A, Rowland V, Huberman B (1974) Neuroscience Res.Program Bull 12.

Kelso JAS, Bressler SL, Buchanan S, DeGuzman GC, Ding M, Fuchs A, Holroyd T (1992) Phase transition in brain and human behavior. Phys Lett A 169: 134-144.

Kenet T, Bibitchkov D, Tsodyks M, Grinvald A, Arieli A (2003) Spontaneously emerging cortical representations of visual attributes. Nature 425:954-956.

KoenigT, Studer D, Hubl D, Melie L, Strik WK, (2005) Brain connectivity at different time scales measured with EEG. Phil Trans R Soc B 360:1015-1023.

Kozma R, Puljic M, Balister P, Bollobas B, Freeman, WJ (2004), Lecture Notes in Computer Science 3305:435-443

KuramotoY, (1984) Chemical oscillations, waves and turbulence. Dover Publ., N.Y. 156 p.

Lamme VAF, Roelfsema PR (2000) The distinct modes of vision offered by feed-forward and recurrent processing. Trends Neurosci 23:571-579.

Lamme VAF, Super H, Landman R, Roelfsema PR, Spekreijse H (2000) The role of primary visual cortex (VI) in visual awareness. Vision Res 40:1507-1521.

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

Le vanQuyen, M, (2003) Disentangling the dynamic core: a research program for a neurodynamics at a large scale. Biol Res 36:67-88.

Libet B (2004) Mind time: the temporal factor in consciousness. Harvard University Press, Cambridge, Mass. 248.p.

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

Lumer ED, Edelman GM, Tononi G (1997) Neural dynamics in a model of the thalamocortical system. I. Layers, loops, and the emergence of fast synchronous rhythms. Cereb Cortex 7:207-227.

Lutz A, Lachaux J-P, Martineri J, Varela FJ (2002) Guiding the study of btain dynamcs by using first-person data: synchrony patterns correlate with ongoing conscious states during simple visual tasks. Proc Natl Acad Sci USA 99:1586-1591

Mahner M, Bunge M (1997) Foundations of Biophilosophy. Springer, New York.

Murthy VN, Fetz EE (1992) Coherent 25-35 Hz oscillations in the sensorimotor cortex of awake behaving monkeys. Proc Natl Acad Sci USA 89:5670-5674.

Newell A (1994) Unified theories of cognition: The William James Lectures, Harvard University Press, Cambridge Mass. 549 p.

Newman J, Baars BJ (1993) A neural attentional model for access to consciousness: a global workspace perspective. Concepts in Neuroscience 4: 255-290.

Newman J, Baars BJ, Cho S-B (1997) A neural global workspace model for conscious attention. Neural Networks 10:1195-1197.

Newman MEJ (2003) The structure and function of complex networks. SIAM Review 45:167-256.

Pikovsky A, Rosenblum M, Kurths J (2001) Synchronization : a universal concept in nonlinear sciences. Cambridge University Press, Cambridge. 411 p.

Rapp PE (1986) Oscillations and Chaos in cellular mebaolism and physiological systems, In: AV Holden, ed., Chaos. Machester University Press. pp.179-208.

Ribary U, Ionnaides AA, Singh KD, Hasson R, Bolton JPR, Lado F, Mogilner A, Llinas R (1991) Magnetic field tomography of coherent thalamocortical 40-Hz oscillations in humans. Proc Natt Acad Sci USA 88:11037-11041, 1991.

Roelfsema PR, Engel AK, Koening P, Singer W (1997) Visuomotor integration is associated with zero-lag synchronization among cortical areas. Nature 385:157-161.

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

Schmolensky MT, Wang Y, Hanes DP, Thompson KG, Leutgeb S, Schall JD, Leventhal AG (1998) Signal timing across macaque visual system. J. Neurophysiol. 79:3272-3278.

Sergent C, Dehaene S (2004) Is consciousness a gradual phenomenon ? Psychol Sci 15:720-728.

Sigman M, Dehaene S (2005) Parsing a cognitive task: a characterization of the Mind's bottleneck. PLoS 3(2), e37.

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

Singer W (1998) Consciousness and the structure of neuronal representations. Phil Trans R Soc Lond B , 353:1829-1840.

Sporns O, Tononi G, Edelman GM (1991) Modeling perceptual grouping and figure-ground segregation by means of active re-entrant connections. Proc Natl Acad Sci USA 88:129-133

Sporns O, Tononi G, Edelman GM (2000) Connectivity and complexity: the relationship between neuroanantomy and brain dynamics. Neural Networks 13:909-922.

Sporns O, Koetter R (2004) Motifs in brain networks. PLoS Biology, 2(11): e369.

Sporns O, Chialvo DR, Kaiser M, Hilgetag CC (2004) Organization, development and function of complex brain networks. Trends in Cog. Sci. 8:418-425.

Sporns O (2004) Complex neural dynamics. In: VK Jirsa,& JAS Kelso, ed. Coordination Dynamics: issues and trends. Springer, Berlin. pp. 179-215.

Tallon-Baudry C, Bertrand O (1999) Oscillatory gamma activity in humans and its role in object representation. Trends Cogn Sci 3:151-162.

Taylor, JG, Alavi FN 1993), Mathematical analysis of a competitive networks for attention. In: JG Taylor, Mathematical Approaches to neural networks, Amsterdam: Elsevier Publ., pp.341-382.

Thom R (1983) Structural stability and morphogenesis; an outline of a general theory of models. Halstead Press, N.Y. 305 p.

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

Tononi G, Edelman GM (2000) A Universe of consciousness: how matter becomes imagination. Basic Books, N.Y.

Tononi G, Sporns O, Edelman GM (1992) Reentry and the problem of integrating multiple cortical areas: Simulation of dynamic integration in the visual system. Cereb Cortex 2:310-335.

Tononi G, Sporns O, Edelman GM (1994) A measure for brain complexity: relating functional segregation and integration in the nervous system. Proc Natl Acad Sci USA, 91:5033-5037.

Tononi G, Edelman GM, Sporns O (1998) Complexity and coherency: integrating information in the brain. Trends Cogn Sci 2:474-484.

Tononi G, Sporns O (2003) Measuring information integration, BMC Neuroscience 4:31 available at: http://www.biomedcentral.com/1471-2202/4/31 .

Varela F, Lachaux J-P, Rodriguez E, Martineri J (2001) The brainweb: phase synchronization and large-scale integration. Nat Rev Neurosci 2:29-239.

von der Malsburg Ch (1981/1994) The correlation theory of brain function. In: E. Domany, ed. Models of neural Networks, Springer NY. pp. 95-119.

von Stein A, Sarntheim J (2000) Different frequencies for different scales of cortical integration: from local gamma to long range alpha/theta synchronization. Int. J. Psychophysiol. 38:301-313.

Wallace R (2005 a) Consciousness: a mathematical treatment of the Neuronal Global Workspace Model. Springer, NY. 116

Wallace R (2005 b) A modular network treatment of Baars' Global Workspace consciousness model (Version 7.2). available at: http://cogprints.org/4578/

Wallace R (2005 c) A Global Workspace perspective on mental disorders, Theoretical Biology and Medical Modeling. available at: http://www.tbiomed.com/content/2/1/49)

Wallace R (2006) Generalized inattentional blindness from a Global Workspace perspective. available at: http://cogprints.org/4719/01/gorilla4.pdf

Werner G (2005) Perspectives on the Neuroscience of Cognition and Consciousness. BioSystems, in print

Yeomans JM (2002) Statistical mechanics of phase transitions. Clarendon Press Oxford. 153 p.

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