

Perspectives on the Neuroscience of Cognition and Consciousness.

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Summary

The origin and current use of the concepts of computation, representation and information in Neuroscience are examined and conceptual flaws are identified which vitiate their usefulness for addressing the problem of the neural basis of Cognition and Consciousness. In contrast, a convergence of views is presented to support the characterization of the Nervous System as a complex dynamical system operating in a metastable regime, and capable of evolving to configurations and transitions in phase space with potential relevance for Cognition and Consciousness.

Introduction

The conceptual framework of this essay is predicated on John Searle's philosophical stance of biological naturalism (1983,1992): specifically, conscious states are entirely caused by lower level neurobiological processes; and they are "realized in the brain as features of the brain system, at a higher level than that of neurons and synapses" (Searle, 2004). The features designate subjective states of sentience or awareness. My main objective in the following is to propose a neurobiological process for the realization of the features: the issue at stake is to assemble neurobiological evidence that would support an account for the origin of the features' qualitative novelty as a state space transition, according to principles of nonlinear dynamics in complex physical systems.

In the context of this essay, I will consider Cognition and Consciousness as subjective states of sentience and awareness (Searle, 1992); and, when speaking of Neuroscience, I will limit the consideration of empirical data to the kinds obtained with neurophysiological and neuroanatomical methods, omitting for the purposes of this essay the enormously important areas of neurochemistry, molecular biology and neuro-genetics

Before turning to the main objective, it will be necessary to clear the way and remove obstacles with foundational issues in Neuroscience which, I submit, lie in the way of meaningfully addressing issues in Cognition and Consciousness. This will complement Searle's (1998) list of philosophical obstacles to studying Consciousness scientifically. I take my cues from Ian Hacking's (1985) "Styles of Scientific Reasoning", tracing currently prevalent discourse practices of Neuroscience from their enticing origins and initial plausibility to becoming sources of conceptual confusion and to precluding viable alternatives.

With a nod to Foucault: a kind of Archeology of Neuroscience

The time frame for close scrutiny is quite short: with the outline of the classical Neuron doctrine firmly established, much basic Neuroanatomy and clinical Neuropsychology ascertained, and the essence of neurohumoral transmission and the ionic mechanism of neuronal electrical activity essentially in place, the field was by the mid 1940s ripe for assimilating novel ideas and technical advances that promised entirely new horizons for conceptualizing the Nervous System. These were forthcoming in rapid succession: Norbert Wiener's Cybernetics with the notion of feedback and control; Shannon's Information Theory; the invention of the Turing machine and the formulation of the Church-Turing's Thesis; the construction of the first large electronic computers, and von Neumann's invention of their programmability. Ling and Gerard demonstrated the use of micro electrodes to record electrical activity from individual neurons in the brain, and Adrian (1928) had already shown that single action potential spikes in peripheral nerve fibers transmit action potentials elicited by stimulation of their receptors.

Just imagine the goldmines that suddenly seemed to fall into the hands of system-oriented Neurophysiologists : single neurons and nerve axons delivering a binary code, seemingly just ready made for computing and information transmission in circuits and neural nets with feedback. For me who has experienced these years: the excitement was immense, and the promise seemed unlimited!

For exploring the scientific and social implications of these innovations, the Macy Foundation sponsored a series of annual conferences of the "Cybernetics Group", beginning 1943 and extending for the next 10 years; a virtually unparalleled undertaking. The attendance at the annual meetings varied from time to time, with W. McCulloch usually being in a leading role. Participants, usually 20 or so in number, were drawn from the Sciences of Physics, Mathematics, Biology, the Humanities and the emerging fields of Computer Science and Automata theory. The fascinating story of

these meetings, the substantive discussions and the interpersonal issues that were played out, is told in the Publications of the Josiah Macy Foundation Symposia, in books by Heims (1991, by Dupuy (1994), and in a section of Hayles' "How we became posthuman" (1999). Transcripts of the proceedings were recently published by Pias (2003).

I consider these meetings the birthplace of the "Digital Brain" and origin of the associated influential notions of computation, representation, information, and the single neuron record. Their entrenchment in the Neuroscience discourse was initially quite explicit and in adherence to their original meaning. However, as time passed, their function in Neuroscience became less literal, but as metaphors more insidious. While the judicious use of metaphors can assist at times with intuitively illuminating a target domain (Arbib, 1972), they tend to carry with them the style of reasoning of the source domain which may be (and often is) quite inappropriate for the target; thus entailing the risk of tacitly contaminating the target with erroneous styles of reasoning.

The thrust of the following arguments is critical with a view of exposing conceptual flaws and neurobiologically unwarranted application of terms and ideas beyond their original sense, mostly from the physical sciences. This must not detract from the fact that the experimental work *per se* to which the investigators applied these notions, is frequently of the highest caliber, and deserving of admiration for ingenuity of experimental design and execution. My quarrel is with a single-minded interpretation of results and the discourse in which they are framed. For the investigators' jargon in 'the life of the laboratory', this is probably of lesser consequence, except for the price of excluding alternative theoretical frames which would have directed the research into different, possibly more revealing, channels.

It may be helpful to illustrate this point with a case study of multiple conceptual interpretations of the same kind of experimental data: Mountcastle & Werner, 1964; Werner & Mountcastle, 1963) recorded action potentials in single afferent nerve fibers and sensory neurons in response to precisely measured mechanical stimulation of peripheral receptors. In the first place, we determined the correlation function between stimulus strength and neural activity, the latter as frequency in bins of various duration. We then subjected the same data to analysis in three different conceptual frameworks: as a psychophysical (Weber) function, as a statistical decision process on distribution functions of static responses, and as information transmission from the stimulus to the neural-response domain. What I am advocating with this example is the possibility, under suitable conditions, to interpret one and the same set of experimental observations in multiple theoretical frames of reference, each reflecting a different theory of nervous system function (Werner, 1985). This is an example of interdependence of theory and neural data (Hardcastle & Stewart, 2003).

The real problem arises with the study of Cognition and Consciousness when the neuroscience reports are taken at their face value outside the laboratory of origin: it is at

this point that unjustified and misleading generalizations can attribute meaning to the reports beyond the operational aspects of the work itself. Accordingly, these comments are intended for students of Cognition and Consciousness as alerting signals. However, by implication I hope that they may also be of use to the Neurophysiologist for design, planning and data interpretation of new studies.

Despite their close interrelation, I will sketch the evolution of the notions, computation, representation, information and the hegemony of the single neuron from their respective origins to their currently influential form under separate headings, for clarity of exposition.

1: On computation :

In general terms, processes in Nature occur as dynamical systems moving through a state space from an initial to a final state. If this is accomplished by executing algorithms, the process is designated 'computational'. Different kinds of (programmable) computation are conceivable, some differing in very fundamental ways. Initially, the particular type of computation that concerned the Cybernetics group was the special case of the Turing Machine computation. This is also the type of computation that became influential for the Computational Theory of Mind in Cognitive Psychology, for Artificial Intelligence and, for some time, in Neuroscience discourse. As is well known, Turing conceived a minimalist, abstract conceptual machine, designed according to what he thought constitutes the essence of human thinking. Computing with a Turing's device is based on the recursive specification of a procedure by which a given type of problem can be solved in a finite number of mechanical steps. Such a conceptual machine permits the precise delineation of the type of computing tasks it can in principle execute, and what the requirements are.

In actual practice, Turing machine computation (like any other form of programmable computation) is a physical process which transforms abstract objects by syntactic rules into new abstract objects. This is accomplished by a human user assigning symbolic tokens representing physical states in the world to bit configurations in the electronic processing level of the machine, and applying symbolically encoded transformation rules. If machine input and rules are properly chosen, machine configuration will be attained which can be interpreted to reflect new states in the world. The amazing (and seductive) fact is that the laws of physics governing the electronic machine configuration permit the mechanical execution of human mental algorithms. The common computer jargon of "rule-governed operation" is misleading and obscures the facts. Loading a rule into the processor transforms it into a physical state which can be interpreted by the user as 'rule following'. But as far as the physical device of the computer is concerned, it works as a collection of circuits which operate

according to physical laws. Thus, the behavior of the machine is influenced in a systematic way by the meaning of the syntax the user supplied (Hayes, 1992). Thus, this form of programmable computation is intrinsically not a natural process. Rather, it is a case of putting Physics in the service of human syntax and semantics.

Few, if any, Neuroscientists still consider this form of Computation relevant for the function of the Nervous System. Alternative paradigms such as combinatorial-state automata and connectionist networks have consolidated in due course to the field of Computational Neuroscience for simulating neurophysiological and psychological processes (Churchland et al.,1990).

But this merely defers the question: can the brain be assigned a computational interpretation, for instance in the form of executing algorithms on some distributed neural network architecture or implementing some computable mathematical function? Searle (1992) is careful to distinguish this question from the alternative: “Can the operations of the brain be simulated on a digital computer?”. For Copeland (1996) this is an empirical question, while Searle’s answer is principled on the fact that “syntax is not intrinsic to physics”.

Those who believe in assigning intrinsic computational functions to neural structures tend then to speak of the brain (or some neural subsystem) as a “computational information processor”; a notoriously vague notion, apparently first introduced without clarification or definition in David Marr’s (1982) monumental, though eventually futile computational program of the visual system (Sayre, 1986). Although of frequent use in Neuroscience discourse, ‘information processing’ is an expression that requires some clarification (see Section 3).

The project of Computational Neuroscience retained from the Cybernetics group the notion of representation in computation. Accordingly, the belief in computational information processing by the brain (or some neural subsystem) necessarily requires the additional assumption of intrinsic states that “stand in” for objects or events in its environment. The topic of representation will be discussed in Section 2.

Computational Neuroscience not only defined its own agenda as a sub-discipline within neuroscience. It has also assumed the role of the currently prevalent Theoretical Neuroscience, and has shaped to a considerable degree the experimentalist’s style of reasoning and discourse. The alternative to the Computational Neuroscience perspective is, of course, neural systems merely acting in such a way that their intrinsic function *appear* to an observer as genuinely computational (i.e.: can be computationally simulated). Thus, neural systems, just like any other ordinary physical system (say:

planets in the solar system), would act as if guided by computable functions without themselves computing them, but being amenable to computational simulation.

In the “market place of ideas”, this latter outlook appears currently still less frequently represented. Authors often skirt the issue altogether, leaving the reader in doubt of their personal commitment. Worse still, theory formation in Cognitive Neuroscience and the study of Consciousness can be (and are being) misled by getting the impression from Neuroscience literature that “Computational neuronal information processing” is an established and uncontroversial notion.

2: On Representation

The foregoing section established that a computational view of neural systems requires states that intrinsically represent objects or events in the environment. Accordingly, the concept of neural representation is central to Neurophysiology, but what does it actually mean to say that “a neural signal is a representation”? (de Charms & Zador, 2000). The experimentalist commonly studying functionally more or less separable neural subsystems (in a kind of building-block approach) applies the pre-theoretical assumption of a causal co-variation between a physical event in the world and some identifiable neuronal activity in a structure of the nervous system. The neural activity elicited by the external event is then thought to “stand for” this event as its representation. This notion is usually considered an informal working hypothesis. To become more specific requires defining a measure of neural activity, and analyzing the statistical relationship between the eliciting event (stimulus) and the neural signal and the resultant effect (which may be some overt behavior or a subjective report). The alleged representational signals are carried by neurons in the form of one of several conceivable codes. There is no a priori way of deciding what the code and, hence, the measure of neural activity may be; nor is it always certain whether the experimental stimulus is ecologically meaningful, and -in the case of peripheral stimuli- what mechanical or chemical transduction may intervene between the site of stimulus application and the relevant neural pathway. Frequently, the experimenter has no other choice than selecting neural code and stimulus measure on pragmatic grounds. Pointing out these complexities in the conduct of a simple neurophysiological experiment is intended to forestall all-to-ready acceptance of neurophysiological reports on neural representations for theory formation in the Sciences of Cognition and Consciousness.

On a conceptual level, the experimenter’s practice implies the thesis of Informational Semantics (Dretske, 1981), that is: (semantic) contents of items in the head are constituted by the nomic (causal) relation these items bear to elements in the surrounding world. In this sense, the evoked neuronal response is thought to have representational content (Haugeland, 1991). The corresponding discourse of Cognitive

Psychology claims that intentional content likewise reduces, in whole or in part, to nomic dependency. However, a fallacy becomes readily apparent when considering the customary ascription of content to states of measuring instruments (Grush, 2001): it is dependent on our belief (or knowledge of mechanism) that the informational (representational) content of the device depends lawfully on the state of some other physical entity. Hence, the ascription of content is observer relative. Herein lies the semantic Achilles heel of Computational Neuroscience, and the flaw of the experimenter's style of reasoning: for a third-party observer, there are a dime-a-dozen causal co-variations, but to count as 'representations', they must fulfill a causal role that is intrinsic to the co-varying system. Thus, the experimenter-observed co-variation of neural activity and environmental event does not, in itself, imply that the evoked brain state has representational import. What is required are principled means for determining whether a given neural activity represents something that is independent of the observer's interpretive guesses or knowledge; and why some neural activity 'represents' something, and another does not. Two obstacles stand in the way of Informational Semantics: absence of observer-independent, brain-intrinsic criteria, and conceptual flaws intrinsic to Informational Semantics itself (Bridges, 2005).

To view the brain as 'representing' events in the world in the form of neural activity is also at the root of the misleading, yet recurrent claim of (or search for) a Neuro-Cognitive correlation: according to this 'matching content doctrine' (Noe & Thompson, 2004) the contents of a neural representational system would match the contents of consciousness. What does 'matching content' actually mean? Does the neural system and the subjective experience have the same content, or do the content bearing states merely agree in one or another respect?

Apart from the experimental vagaries, it is thus far evident that "representation", in the computationalist's sense, is at best a flawed, at worst an outright false, concept in the toolbox of the neuroscientist and, thus best disregarded for theory formation in Cognition and Consciousness. But more needs to be said about this in the following.

Rooted in (intelligent) sensory-motor behavior, Brooks's (1991) 'subsumption architecture' in robot design, and similar approaches, dispense with 'representation' altogether. On the premise 'the world is its own best representation', adaptive behavior is guided by direct sensory-motor interaction with the environment. There is no need for internal models. Moment-to-moment interaction with the environment satisfies the requirements for successfully performing and accomplishing tasks in real time. As Clark (1989) put it: "know only as much as you need to know to get the job done".

The general principle of "interactionist" frameworks is the subject of Haugeland's (1995) closely reasoned and subtle conceptual analysis which addresses foundational issues of Cognitive Neuroscience in question. He concludes from system theoretic considerations (the kinds of which he credits H. Simon, 1969), that there is no principled way for viewing brain and environment as separate systems: brain and environment form a nearly-decomposable system (in Simon's terminology). This means in practical terms that the degree of interaction between the brain and environment components of the combined system (i.e. the degree of functional separability into subsystems) can depend on levels of motivation and task priorities. If the behavioral objective is real-time performance in an environment, intimate coupling for direct sensory motor interaction is crucial. If, on the other hand, the agent's interest lies in, say, reflective evaluation of its performance, then decoupling of the system into its components is advantageous. Putting it differently: the coupling coefficient of the brain environment system is a situation and task -dependent variable which can select the system's 'set point' for direct interaction at one extreme, and for "off line" reflective mode, at the other. Haugeland himself stresses integration and functional unity with the environment, including externalized sources of information (like texts, maps etc).

Grush (2004) takes a different approach: his 'emulation theory' postulates the generation of genuine brain-internal representations on principles of control systems architectures. In analogy to sensory-motor control systems, the brain would construct and exploit internal dynamical models of body and environment ('emulators') as an information processing strategy. The return to the emphasis on control systems of the 'Cybernetic Revolution' of the 1940's is of historical interest, as is the resurrection of Craik's (1943) ideas of "the Nature of Explanation".

To summarize this lengthy section: 'Representation' in the original computationalist's sense and in the experimentalist's practice is flawed and of no other than anecdotal value for theory formation in the science of Cognition and Consciousness. It has been expelled from playing a role in the interpretation of many (perhaps most) ordinary cognitive tasks in which the direct interaction with the environment assumes what was thought to be its function. But in a different form, perhaps as emulator for trial actions, rehearsal, and imagination, 'representation' may still occupy a legitimate place, though different from the computationalist's ideas.

3: Information

Shannon (1948) was meticulously careful to delineate the scope of his "Mathematical Theory of Communication" (MTC) as strictly referring to the communication engineer's task: measuring the amount of information that can be exchanged between a transmitter and a receiver; both being in possession of the full

repertoire of signals that can be exchanged. Information, in the sense of MTC is a statistical measure on ensembles, with no reference to semantics of individual messages; relevance is solely expressed in terms of conditional probabilities. Both aspects were all too easily forgotten in the haste to apply the theory to neurological, psychological and social phenomena. McKay, one of the participants at the Macy meetings, insisted on an operational notion of information's use by goal directed systems, and in meaning as an other than statistical relationship between message and recipient. His criticism of indiscriminate application of MTC outside the range for which it was intended failed to prevail in the sometimes heated arguments. His views are set forth in a very thoughtful though generally neglected book (MacKay, 1969). The subsequent efforts to assimilate "Information" into conceptualizing Mind and Meaning (Adams, 2003) have not made major inroads into what A.R. Anderson called in 1964 "a scandal in Philosophy" .

How did MTC spawn "Information Theory" and "Information Processing" (see section 1)? Shannon's approach in MTC can be dissected into several steps: the first is about defining a measure of how much (little) we know of a collective of items, in terms of probabilities of the occurrence of these items in the collective. This is a measure of how uncertain an observer is about the actual composition of this collective, the items of which are categorized by the observer's criteria. Shannon identified this with Boltzmann's Entropy as a measure of order/structure of an ensemble. The second step is: what can this measure tell about comparing two collectives: the source, and another after applying some operation to the source? The change in the recipient collective's Entropy is "*Information*". It is measured as difference in Entropy before and after the transaction; conversely, it is "*Mutual Information*". This much is "Information Theory", as such. We can now look at MTC as *one instantiation* of this scheme, with particular interest in the means by which transmission of Information to the recipient collective occurs via a *channel* that carries "*transmitted Information*". Expressing the various magnitudes in the Binary System reduces all computations to algebraic addition-subtraction. The colloquial use of "Information" does usually not take into account that the technical meaning of 'Information' is inherently contingent on the a priori definition of ensembles.

By a *tour de force*, one may now consider the functioning of the channel as a '*processor of information*', the processing consisting in the effect the channel properties have on Mutual Information. Processing-of-Information-minded investigators can then claim that mutual information between neural structures are the result of processing information. But if not constrained by a specific theory of neural function, they may prefer to adhere to the statistical notion of correlation coefficient.

However, neither method can support or refute on objective grounds what kind of signals ('code') are involved in the interactions of the collectives. (de Charms, 1998).

Note an essential restriction on this scheme that is rarely, if ever, mentioned: we are dealing so far with a closed system, at worst limited by a channels function. In nonlinear systems, such as brains and its sub-assemblies, nonlinearity reigns supremely. Thus, Boltzmann's Entropy must be replaced by Kolmogorov-Sinai Entropy which evaluates the average information loss (gain) with respect to the time development of a trajectory in phase space (Deco & Schurmann, 2000).

Two additional comments are in order: first, categorization of the collectives under consideration and other forms of pre-processing of data for quantitative analysis (e.g.: binning of neural responses, measure of the stimulus continuum, filtering, etc.) are selected and applied by the observer. Therefore, probability assignments for Entropy determination are observer relative, and not intrinsically determined by the biological system under study. The second comment addresses the fact the information is invariably and essentially tied to physical components available in the world and, thus, subject to the laws of Physics (Landauer, 1996). Accordingly, Information amounts to measuring the outcome of physical processes by applying observer-specified procedures on physical states. Information does not have a natural Ontology, and is not intrinsic to the brain.

For Cognitive Science, Bennett & Hacker (2003) have directed their own scathing criticism to the use of Information, information processing, representation, and symbols.

4: the single neuron hegemony:

Finally one more dowry from the Cybernetics Group: the hegemony of the single neuron record. Despite Ralph Gerard's forceful protestations, the single neuron spike as indicator for a binary neural code became the Cybernetic Group's Credo. (Ironically it was Gerard together with Ling who had introduced the technique !) Beginning with the publication of "Mass Action in the nervous system", Freeman (1975, 2000) has repeatedly insisted on and demonstrated the merits of exploring wave patterns at all levels in the brain. Bullock has also on many occasions drawn attention to the dimension of slow electric activity in neural structures. Yet, the primacy of the single neuron code persisted in mainstream neurophysiology until finally, in the late 1980s, challenged by the discovery of synchronized electrical wave electrical activity as a highly specific coordinating link among distributed neurons. About this later.

So much for breaking entrenched styles of reasoning and experimental practices! The recent publication by a group of highly respected senior Neuroscientists, entitled “The neuron Doctrine, Redux” (Bullock et al.,2005) impresses me as a kind of ‘ex cathedra’ final recognition of the multiplicity of factors and possibilities that are operative as integrative and connectivity variables in neural tissue, including also the long neglected Neuroglia.

Does Neurophysiology offer elements for and pointers to a genuine “Cognitive Neuroscience” ?

As a programmatic approach, Gazzaniga & Miller introduced “Cognitive Neuroscience” in 1995 as the title of a publication series. The introduction to the first volume reads: “... Cognitive Neuroscience will be able to describe the algorithms that drive structural neural elements into the physiological activity that results in perception, cognition and perhaps even consciousness”. It is troublesome that this outdated, flagrant functionalist stance was neither corrected nor repudiated in the subsequent volumes of the series and, thus, is liable to distort the perception of this branch of research for the innocent reader. Nevertheless, the name stuck, but care should be taken to avoid contamination with ill-advised and confining definitions of its scope.

Taken as factual reports and stripped of the kinds of conceptual confusions listed in the foregoing section, Neurophysiology has become a vast repository of factual and well defined observations garnered from operationally circumscribed experimental observations. The general notion was (and to a large extent still is) that study of a sufficiently large number of functionally identifiable subsystems will eventually make it possible to synthesize a global theory of the brain. This, I submit, is mistaken; nevertheless, understanding of subsystems imposes at least constraints on global theory formation.

In the following, I select for brief reference those aspects of neural function which, I submit, are the core knowledge that any theory of nervous system function must reckon with.

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 “Darwinian Brain” (Edelman, 1987) is an outstanding demonstration of this. At the neuronal level, neurohumoral and synaptic transmission, the function of dendrites and the manner in which neurons can aggregate to local functional units reveal staggering details, and an enormously large number of degrees of freedom for adaptive modifications.

Neuroanatomy offers solid reference points for important principles of organization. In the first place, many cortical areas, among them primarily the cortical receiving stations of sensory input, are organized in a grid, with surface-perpendicular fiber bundles to grouping neurons to vertical columns, and surface parallel fibers arranged in separate layers. This configuration suggests columnar modularity at a mesoscopic level, intermediate between micro - and macroscopic organization (Mountcastle, 1978), and other iterated modular units (Purves et al, 1992). Second, the layout of cortical areas for sensory function indicate a hierarchic pattern within which multiple links form distinct, yet intertwined processing streams, in concert with direct input from sensory pathways and subcortical as well as brain stem structures [Fellerman & v Essen, 1991]. Finally, multiple reciprocal thalamo-cortical connections form a central core with diffuse projections to the cortical mantle. At a macroscopic level, the organizing principle is a pattern of differentiation and integration (Tononi et al, 1994): the former reflecting the segregation of functionally and anatomically distinct structures and pathways (e.g. the ventral and the dorsal stream in the visual system of primates); the latter constituted by dense systems of reentry (i.e. reciprocally connected) connections which allow for integration of distributed brain functions despite the lack of a central coordinating area. The pattern of long-distance connectivity among multiple cortical and subcortical (Parvizi & Damasio, 2001) connections suggests the designations of “core brain” (Damasio, 1999) and “global workspace” (Baars, 1988; Dehaene & Nagache, 2001). Millions of neuronal groups are linked by an enormous set of convergent and divergent, reciprocally organized connections that form a tight network while still maintaining some local functional specificity. The result is a three-dimensional tangle that suggests that any perturbation in one part of the meshwork will have repercussions throughout its entire extent (Edelman & Tononi, 2001). The functional significance of the multiple interconnections of brain regions is underscored by the recent discovery of breakdown of effective cortical connectivity in sleep, using the tools of transcranial magnetic stimulation and high-density Electroencephalography (Massimini et al., 2005).

Computational Neuroanatomy contributes to the understanding of brain connectivity the identification of cortical connection patterns as a “Small World Networks”, a network architecture associated with resilience to breakdown (Sporns, et al, 2000). The hierarchic aspect of organization places the network of cortical connections into the universality class of “nearly decomposable systems” : perhaps the result of an evolutionary process which, in computer simulations, can be shown to facilitate the achievement of “fitness” (Frenken et al., 1999). The study of complex network organization with implication for Brain theory and Cognition is becoming an

enormously important and promising research area (Sporns et al, 2004; Hilgetag & Kaiser, 2004).

Methodologically, Brain imaging employing positron emission tomography (PET), and functional magnetic resonance imaging (fMRI) is giving access to non-invasive observations on the anatomical location and distribution of neuronal activity under a variety of conditions, including performance of special task by human and animal subjects. For BOLD functional magnetic resonance imaging, Logothetis (2002) secured the most detailed and precise data on what is in fact being measured, with what reliability, and in what relation to other measures of neural activity: the fMRI response correlates well with electrically recorded local field potentials (LFP) of synaptic and dendritic origin, primarily for incoming neural signals and their processing within a region, but not for output signals to the next relay station. Despite this detailed characterization, the temptation to construct a “cognitive Neuroanatomy” on data from imaging studies must be tempered by potential fallacies in interpretation of images (Bogen, 2001) and by the well established recognition of functional degeneracy in neural systems: structurally different mechanisms can be sufficient for execution of a given task, and only their intersection enables identifying the necessary system.

On the horizon I note promising new actors to count with in future: I draw attention to computational simulations of radically novel features of neural microcircuits which function more like liquids responding to perturbations with ripples of waves, rather than like digital gates: an important theoretical insight, but still to be tempered by the realization that mathematical models are not the “real thing” . However, if proven real, such microcircuits would adopt a system dynamics at the boundary region of ordered and chaotic behavior. They would, thus, belong to the class of Natural systems operating at “the edge of chaos”, which are known for their capacity for critical self-organization (Legenstein & Maass, 2005).

I next turn to some aspects of neural function which I will specifically enlist in formulating a conceptual framework of nervous system function with relevance for Cognition and Consciousness. They are subsumed under the heading:

Oscillatory activity, cortical activation patterns and Coordination Dynamics.

I will first address the remarkable discovery of stimulus induced oscillatory and synchronous neuronal activity with the predominant frequency in the 40 Hz range. In sensory systems, the phase synchronization of oscillation is thought to functionally “bind” together neuron groups that respond to identical stimulus features, thus forming in some sense a higher-order neuron assembly (Gray & Singer, 1987, 1989; Eckhorn et

al, 1988). Synchronization can occur across distances of several mm and also across different cortical regions (Roelfsema et al.,1997; Ribary et al.,1991). The functional neuron assemblies thus formed consist of elements which are distributed in space, but 'locked' together by a common signal phase. Physiological data suggest that the synchronous oscillations are mediated by cortico-cortical connections which link preferentially cortical neuron columns responding to related stimulus features and tending to be grouped perceptually (for review: Singer, 1998, 2004). Synchronous cortical oscillations also seem to have a preparatory function in the generation of motor output (MacKay, 1997).

Detailed analysis of the local field potentials constituting this phenomenon established that the duration of oscillatory responses is short (their duration having an exponential distribution), and interrupted by epochs of stochastic activity (Murthy & Fetz, 1992). In the sensory motor cortex of awake monkeys, activity of some neurons as far apart as 14 mm were found to be synchronized with each other and with the local field potentials. Most striking is the virtual simultaneity and the very short latency of onset in the oscillating ensemble, suggesting a process operating on a faster time scale than conduction and synaptic delays would permit (Singer et al, 1997).

The unusual properties of this oscillatory activity suggest a process of principled significance for brain theory. Simulation studies of neural assemblies identify the switching phenomenon as a phase transitions due to synaptic nonlinearity and fluctuations from peripheral input and/or interaction with other assemblies (Bauer & Pawelzik ,1993). This places the cortical oscillatory activity in the category of Kuramoto's (1975) "self-synchronization transitions" in an ensemble of oscillators. This phenomenon has been identified in a variety of biological systems as a mode of self-organization. Phase transitions in nonlinear dynamic systems occur as a matter of principle with very short latency. They would then also account for the short onset latency of the assembly oscillations. These considerations identify the oscillations in the 40 Hz range, and their apparent role in perceptual and motor functions, as manifestation of self-organizing nonlinear system properties of neuronal ensembles.

A diverse array of data speaks to an intricate dynamics of surprisingly long lasting activity patterns of appreciable spatial extent, set in motion by a sensory event or in task situations. In the first place, conventional single neuron recording has established the time course of signal distribution across the multiple cortical areas of the visual system, extending over some 150 msec from time of onset of stimulus. The sequence of activation departs drastically from what one would expect if the cortical regions were activated sequentially in the order of pure hierarchy: for example, LFP activity in Visual area V4 has a latency much larger 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 discerned 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 & 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 (Fox et al., 2005, suggesting a cortical network of intrinsically anticorrelated components. In perceptual tasks, synchronous LFP oscillations of frequencies from 12 to about 80 Hz reflect sequential patterns of co-activation of different brain regions, extending up to 500 msec in successful (but not failed) discrimination performance (Bressler, 1995; Rodriguez et al., 1999; Ding et al., 2000), with different neuronal assemblies evolving in different frequency ranges (von Stein & Sarntheim, 2000). In binocular rivalry in Humans, locally and globally synchronized neuromagnetic activity is associated with perception of the stimulus, but absent when not perceived (Srinivasan et al, 1999; for a review of related studies: Blake & Logothetis, 2002). Finally, brain imaging during natural viewing conditions contribute an insight into the temporal organization (“chronoarchitecture”) of brain activity since functionally different brain regions exhibit individually distinct temporal activity patterns. (Bartels & Zeki, 2004).

In the following, I turn to an application of the principles and tools of Coordination Dynamics to brain function, and to suggestive evidence for its conceptual contribution to Cognition. Coordination Dynamics of complex systems studies the manner in which states of interdependency among the system’s components change with time (Bressler & Kelso, 2001; Varela et al., 2001). In the application of this approach to the brain, the phase relationship of local field potentials (LFP) is taken as the significant collective variable for ordering the sequence of activation patterns in time and distribution in space. Unlike the msec and mm range of local coordination, times extend up to several 100 msec, and spatial interdependence may encompass diverse cortical and subcortical zones, and the brain stem.

Methodological refinements have made it possible to examine very precise relationships between electrical brain activity and perceptual-cognitive behavior. High speed Electroencephalography and Magneto-Encephalography (MEG) supply data for such refined analyses: arrays of superconducting quantum interference devices (SQUID), placed on the scalp, give access to the spatial-temporal patterning of magnetic fields generated by intracellular dendritic current flow, with millisecond responsiveness. A brief description of a typical experimental protocol (Kelso et al,

1992) that applies this method will clarify the principle more clearly than an abstract description: the human subject's task is to flex the right index finger in response to brief tones; the frequency of the tone blips is stepwise increased from .025 to 3.25 Hz. The task is to make the finger movement between consecutive tone stimuli. At a particular repetition rate of the of the tone blip (e.g. 1.75 Hz) the anti-phase, syncopated, finger movement changes automatically to a synchronized in-phase coordination. Concurrently, activity of the SQUID sensors on the skull changes from one spatial-temporal pattern to another. The essential point of this demonstration, which is representative of many similar studies of "Coordination Dynamics" (Bressler & Kelso, 2001) is that both behavior and brain activity undergo a sudden transition from one stable state to another at a critical stimulus repetition. This phenomenon is thought to attribute to the brain the universal property of complex systems operating in a metastable dynamics, far from equilibrium.

Evidence for the brain's metastability is also forthcoming from a recent study of Freeman & Holmes (2005), based on the analysis of spatio-temporal patterns in the 12-80 Hz band of the Electroencephalogram. Metastable dynamics is thought to result from a balanced interplay of functional integration and segregation as a reflection of a system's complexity (Tononi et al, 1994).

Behavior, Cognition and Consciousness: manifestations of critical transitions in a neural system's phase space evolution ?

The viewpoint of Dynamical System Theory is fundamentally geometric in terms of points, trajectories and regions in a space of possible states. Collectively, they describe the system flow (or evolution) whose shape is determined by the system's intrinsic dynamics in interaction with external perturbations. Much can be learned from this qualitative perspective because of the universality of certain properties of dynamical systems: this is possible because dynamical system theory has established classes of systems with typical properties (e.g.: types of coupling of oscillators, types of instabilities etc). Identifying from some observed properties of an empirical system to which class it belongs makes then generalizations and predictions possible, beyond those which may actually be observable. (Note that I have applied this principle when generalizing from observed state transitions to properties of the class of complex systems far from equilibrium).

In Nature, phase space dynamics is a physical process, guided by the physical forces that are intrinsic to the interactions among the system's components with forces that may impinge on it from outside. Mahner & Bunge (1997) consider phase space (state space) an ontological fundamental in Biophilosophy. For purposes of

computational simulation, continuous (differential equations), neural networks or discrete (mapping) methods can be applied which may then allow also reductionistic explanations if empirical values can be assigned to certain variables in the simulation.

Of prime interest for present purposes is the spatial-temporal dynamics in response to perturbation by environmental (sensory) events. Complex systems consisting of many interacting components can be visualized as occupying regions in the system's "phase space" of as many dimensions as there are independent components; each component being a point in that high dimensional space, and contributing to the definition of its shape. The time evolution of the system, spontaneously or under perturbation, can then be tracked as movement and configuration change of the system's phase space representation. Note that 'representation' is in this use a mathematical-topological abstraction.

Configuration change of the state space may be due to change in component properties and/or new interaction patterns among components. In its course, the phase space representation may undergo an abrupt change at a critical point, including change in dimensionality. Such singularities are manifest as state transitions at the system's macroscopic level: at some critical point, the system self-organizes itself abruptly to another stable state. One speaks then of self-organized criticality (Bak,1996). Under certain circumstances, the system may vacillate between the phase space configurations: the macroscopic behavior which it displays under this condition is then classified as metastable. Metastability may arise spontaneously because of some random fluctuations, or as the effect of a change of a "control parameter" of the system's phase space dynamics

Several suggestive though in no way conclusive lines of support can be adduced. In the previously cited observation by Kelso et al, the frequency of the auditory stimulus acted as a control parameter for triggering an abrupt transition in behavior and EMG. The conditions for and pattern of changes meet the expected behavior of state transitions in complex dynamic systems: a sudden bifurcation from one stable pattern to another, at a critical point of the behavior controlling stimulus. The notable feature of the observations is the simultaneity of the transition in the subject's motor behavior and in the EMG. This experiment is paradigmatic for a large number of similar studies inspired by H. Haken's (2004) theory of Brain Dynamics (Synergetics) which applies the general considerations of system dynamics to brain-behavior relations with a high degree of mathematical sophistication.

In a series of studies, Dehaene, Changeux and associates (1987, 1994, 1998, 2003) have developed neural network architectures designed for simulating various

psychological functions. Their approach is based on a form of “global workspace” (Baars, 1988; Dehaene & Nagache, 2000) of distributed neurons with long distance and reciprocal connectivity that can potentially link multiple specialized brain areas in a coordinated though dynamically variable manner. Initially, their assumption was that intense mobilization of this central core would be associated with a subjective feeling of conscious effort (Dehaene et al, 1998). Subsequently, these authors came to interpret a transition to conscious processing in terms of a bifurcation in the phase space of the simulated network (Dehaene, Sergent, Changeux, 2003). On different premises, Neural Networks with critical phase transitions have also been designed by Stassinopoulos & Bak (1995) and tested as “critical brain networks” by Chialvo (2004).

Recall from the previous section the spatial-temporal evolution of the activity pattern in an experiment of brain imaging, observed for about 150 msec, and also the sequence of waxing and waning activation patterns in cortex, following visual stimulation. Unfolding patterns of phase synchrony in various perceptual and behavioral situations lasted for several hundred msec. To formulate such observational data in phase space terminology is essentially re-describing them, except in a framework which allows new kinds of inferences and predictions. Thinking in terms of phase space evolution, the time course of evolution of the state space representation is surprisingly slow. But recall that it takes some 500 msec in human subjects for a stimulus to the somatosensory 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 (Backmann, 2000).

The array of empirical data and conceptual points of view assembled in the foregoing sections motivate me to propose that conscious experience is a macrolevel manifestation of neural activity in the brain phase space, as it evolves to a critical transition. It would then be necessary to assume that evolution of a phase space representation to a metastable transition (bifurcation) for conscious experience occupies several hundred msec. If there is any merit to this suggestion, it would have significant consequences for the experimenter: trajectories of phase space evolution in brain space and time would serve as the genuinely informative neural data, in concert with subjective reports or expression in behavior.

What is missing is tying loose ends together with an experimental design which, though difficult, is feasible and could be fairly conclusive: obtain brain images serially

after stimulation, reconstruct from the images the phase space representation, look for sudden transitions and their timing, and relate this to the verbal report (or behavioral expression) of a sensory experience. Simultaneity of a subjective experiential report and a singularity in the phase space evolution of the MEG would suggest an affirmative answer to the question posed in this section's title.

A striking feature of most scenarios cited in this section is the occurrence of synchronous oscillatory activity in neuron pools of varying size. Synchronicity is not unique to the nervous system. It can be observed in numerous biological systems: e.g. glycolytic and other metabolic cycles, pacemaker cells in the heart, kidney nephrons, cycles in cell division, even predator-prey cycles; many more examples can be found in Winfree (2000). Synchronization is virtually ubiquitous in biological systems in which the activity of components benefits from being coordinated. Collective Synchrony can be accounted for by the physical mechanism of Kuramoto's process of Self-synchronization transition (1984): Consider a system of oscillators whose natural frequency is distributed over a certain range; and where phase randomizing forces (noise) are at work but opposed by the coupling among oscillators, favoring synchrony; the case of opposing forces as condition for phase transitions. Emergence of Synchrony then is another instance of phase transition (bifurcation). The coordination of synchrony over the ensemble unfolds in stages; beginning with a few oscillators becoming synchronized, a mean field forms that drives other oscillators to synchrony. Note the circular causality of self-organized criticality: oscillators staging the mean field which recruits more oscillators which contribute to the mean field: the case of circular causality which Haken (2004) describes as "enslaving principle". The important point is that this mechanism not only organizes synchronicity but then also ensures the precision of its maintenance. This is also a juncture at which propagating slow wave potentials and synchronicity of oscillators interact (Ermentrout & Kleinfeld, 2001).

The framework of brain function proposed here resonates with a visionary idea of Katchalsky et al, some 30 years ago (1974). At the end of a program on Dynamic patterns of brain cell assemblies, he concluded 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 neurophysiology". Along similar lines, though more specific, H. Haken formulated in 1983 the hypothesis of the brain being a self-organizing pattern forming system that operates close to instability points, which allows it to switch flexibly from one coherent state to another. Still earlier, Ashby, a Cybernetician but not a member of the Cybernetics group proper, proposed already in 1952 that brain phenomena might be accounted for by dynamical system models.

Closing the loop

I started with sketching what Neurophysiology may be able to bring to the table for exploring neural function in Cognition and Consciousness, and I ended with a framework of how one might think about this: a heuristic that may be worth a closer look. Though possibly defeating myself, I want to supplement this with an additional message to the Psychologist and Philosopher: *caveat Neuroscientist* ! Much of current Neurophysiology is infested with the misconceptions and faulty styles of reasoning I addressed initially. Worse still, very often, it does not heed its own most important accomplishment: that the brain must be understood as a complex system, responding and acting at any time as a whole (or at least with much of it). Punctate measurements of neural functions at one or another site and at one point in time, in isolation and disregard of its relation to other sites, misses the evolution of the neural process in space and time which, under the notions discussed here, is an essential aspect of Cognition and Consciousness. I have previously addressed this same shortcoming for studies with single neuron recordings in experimental learning tasks (Werner, 2004)

Beyond the brain ?

Beginning with the mid 1990s, the dynamical perspective reached some degree of prominence in Cognitive Science (van Gelder &Port, 1995; Giunti, 1997). The rapid growth of the relevant literature of which a detailed account extends the scope of this essay, reflects the central notion that a cognitive agent must be viewed as coupled with the world in reciprocal interaction. What matters for this style of reasoning is that an embodied, situated, enactive agent together with its environment constitute a cognitive system: the blurring of boundaries between perception and action, and between mind and the world are among the key issues (Hurley, 1989; Noe, 2004) Once embarked on this course, the next question arises: "where does the mind stop and the rest of the world begin?" (Clark & Chalmers,1998). With this question, the authors draw attention to the numerous external resources used in support of Cognition. Bio-Musicologists have gained access to at least one form of interaction with external resources by studying the coupling between the phase space structure of music and electrical brain events (Wallis, 1991). More recently, Patel & Balaban (2000) found temporal patterns of electromagnetic activity in the left posterior hemisphere of humans, which track the pitch contour of tone sequences with melody-like statistical properties (Boon & Decroly, 1995). The role of this phenomenon for shared interpersonal experiences (Benzon, 2001) also warrants attention.

Dare I ask an impertinent question: “what is Consciousness without the world“? Could it be contingent on levels of interactivity, rather than exclusively the capacity of a brain in isolation?

Wherever the boundaries may lie within which the brain can act as the medium of Cognition and Consciousness: it is in the proposed framework of Neuroscience equipped to seamlessly join its own phase space with that of a larger and more encompassing system.

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