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Indirect biological measures of consciousness from field studies of brains as dynamical systems

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Abstract

Consciousness fully supervenes when the 1.5 kgm mass of protoplasm in the head directs the body into material and social environments and engages in reciprocity. While consciousness is not susceptible to direct measurement, a limited form exercised in animals and pre-lingual children can be measured indirectly with biological assays of arousal, intention and attention. In this essay consciousness is viewed as operating simultaneously in a field at all levels ranging from subatomic to social. The relations and transpositions between levels require sophisticated mathematical treatments that are largely still to be devised. In anticipation of those developments the available experimental data are reviewed concerning the state variables in several levels that collectively constitute the substrate of biological consciousness. The basic metaphors are described that represent the neural machinery of transposition in consciousness. The processes are sketched by which spatiotemporal neural activity patterns emerge as fields that may represent the contents of consciousness. The results of dynamical analysis are discussed in terms serving to distinguish between the neural point processes dictated by the neuron doctrine vs. continuously variable neural fields generated by neural masses in cortex.

Keywords: Action–perception cycle; Arousal; Attention; Attractor landscape; Consciousness; Criticality; Electroencephalogram (EEG); Fields; Intention; Phase transition; Wave packet

1. Introduction

Dynamical systems are collections of entities that organize themselves into continually changing groups by exchanging matter and energy. Examples range in scale from molecules of air and water creating hurricanes to citizens creating committees. Dynamical brain systems likewise range from quantum excitation of receptors to molecules that organize into DNA, proteins and membranes to people collectively creating tribes and teams. Entities that support consciousness operate simultaneously as a seamless whole across the entire range. Owing to their diversity the scientific study of these entities requires measurement at different scales of time and space. Each study has its own experimental paradigm and theory by which to relate brain structures and functions to consciousness through behaviors. Physiologists record trains of action potentials of axons and local field potentials (LFP) of dendrites in relation to perceptions reported by subjects of objects and people; they explain their findings with help from anatomists using Golgi stains to reveal neurons in networks and sophisticated histochemical techniques that reveal large-scale neural organization. Neurochemists and pharmacologists collaborate with electron microscopists and geneticists to analyze the ultrastructures of membranes, vesicles and DNA in order to understand the hereditary and experiential determinants of memory. Psychologists and engineers correlate behaviors with noninvasive brain images of regional variations in blood flow, the concentrations of chemicals (glucose, oxygen, hemoglobin, radiolabeled neurotransmitters), magnetic fields (magnetoencephalogram, MEG) and electric fields (electroencephalogram, EEG) in order to localize cortical and nuclear modules that are coactive with intentional behaviors. Sociologists use clinical observations on subjects with neurogenetic or drug-induced disorders of brain functions to explain maladaptive behaviors and altered states. Every reflex and intentional act and thought is based on the

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exchanges of matter and energy through neural activity at every scale.

Our need to comprehend the mind-boggling diversity of forms and scales of matter and energy and their rates of change imposes the requirement for a universal language with which to describe relationships among them. That language is mathematics. In research by my groups over the past half century we have constructed one such language, a hierarchical system of differential equations called Katchalsky models ("K-sets") which are designed and parameterized using anatomical, pharmacological, and physiological data, and which serve to simulate and explain virtually all of our experimental observations on brain activity in relation to behavior (Freeman, 1975, 2000; Kozma & Freeman, 2001; Kozma, Freeman, & Erdí, 2003; Principe, Tavares, Harris, & Freeman, 2001). This is not to say that the language of brains is mathematics. The leading 20th century mathematician John von Neumann wrote: "... the mathematical or logical language truly used by the central nervous system is characterized by less logical and arithmetical depth than what we are normally used to. ... We require exquisite numerical precision over many logical steps to achieve what brains accomplish in very few short steps. ... Whatever the system is, it cannot fail to differ considerably from what we consciously and explicitly consider as mathematics [1958, pp. 80–81]". Rather, mathematics in many forms provides tools that investigators use to measure and represent the relations of brain functions to behavior, cognition, and consciousness.

Although differential equations form the core of my inferences, like other skeletons they are best relegated to the closets of appendices and monographs. My aim in this essay is to describe in words my view of brain dynamics with the particular intent of explaining some properties that are inferred for consciousness. My Introduction and Section 2 list the major levels of brain function in consciousness and give examples of the state variables at each level, representing the *substances* of consciousness and leading to discussion of the relations and transpositions of measurements across levels. Section 3 contrasts descriptions of brain operations on the one hand in terms of information carried by action potentials and on the other hand in terms of knowledge fragments expressed in fields of neural activity that are manifested in epiphenomenal electric and magnetic field potentials (EEG and MEG), which support discussion and comparison of the reflex arc and the action–perception cycle representing basic neural *machineries* of consciousness. Section 4 takes up the problems posed by intentional action and proposed solutions in terms of self-stabilizing background activity and the formation, transmission, and integration of self-organized spatiotemporal patterns of goal-directed brain activity that may represent the *contents* of consciousness. Section 5 summarizes implications of dynamics for further specific *properties* of consciousness.

There are severe constraints on what can be achieved with this neurodynamical approach to consciousness. There is no universally accepted definition of consciousness or agreement on variant types, levels and altered states. There is no physiological measure or index of consciousness. The only test available is to ask a subject: "Are you conscious now, and do you remember being so in the past?" Animal subjects that provide functional data cannot pass this test, and no one has yet succeeded in proving precise neural correlates in humans of verbal or otherwise symbolic reports of self-referential experiences. Therefore my remarks on properties of consciousness refer to a state that I conceive to exist in animals and small children before they can talk. I leave the 'hard problem' (Chalmers, 1996) to philosophers and limit my comments to some not-too-surprising biological properties that I conceive as emergent from modeling brain dynamics, namely that consciousness arises in a very small and intermittent fraction of the variance from the enormous groundswell of widely distributed background brain activity in intentional states; that the contents form entirely by endogenous construction of macroscopic patterns ultimately from microscopic cellular input and not by import of forms through the senses; that the contents are in fields that are globally distributed over each hemisphere though neither uniformly, homogeneously, nor reproducibly; that the stream of consciousness is cinematographic rather than continuous, with multiple frames in coalescing rivulets; that its action in respect to contents is judgmental rather than enactive, so that its prime role is not to make decisions but to delay and defer action and thereby minimize premature commitment of limited resources. This aspect is couched in the adage: "stop and think before acting".

There remains the question whether it might be possible to put forward in the biological context an acceptable definition of consciousness that incorporates the subjective, experiential property of consciousness. While for many philosophers consciousness poses an enigma and a mystery (Searle, 1995), there is no doubt about the immediacy and primacy of the experience, which strongly resembles our experience of diverse kinds of force and energy, whether inertial, gravitational, electric, thermal, etc. We can only indirectly experience forces by observing their effects on persons and objects that are accessible to our sensory and perceptual neural mechanisms. We measure each kind of force by its effects on objects in motion. In this essay I pursue this analogy and come to the conclusion that consciousness is not merely 'like' a force; it *is* a field of force that can be understood in the same ways that we understand all other fields of force (and energy) within which we, through our bodies, are immersed, and which we, through our bodies, comprehend in accordance with the known laws of physics.

2. The flow of activity through dynamical systems and its description as information

The study of brain activity at every scale must include measurements of intentional and voluntary behaviors, if the tables, graphs and illustrations that display the properties of molecules, organelles, neural networks, populations, modules, and large-scale brain systems are to be meaningful. The difficulties of that search for meaning are reflected in the conflicts and uncertainties that are encountered in the search