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

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**Key words:** action-perception cycle; arousal; attention; attractor landscape; consciousness; criticality; electroencephalogram (EEG); fields; intention; phase transition; wave packet

#### **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.

#### **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 in 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 and Freeman, 2001; Principe et al., 2001; Kozma, Freeman and Erdí, 2003]. This is not to say that the language of brains is mathematics. The leading 20<sup>th</sup> 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 for the neural correlates of consciousness. There are wide explanatory gaps between observations of brain activity and verbal reports of

phenomenological experiences and intended or voluntary actions. Dynamical systems theory may help to bridge those gaps and demonstrate the relevance of the pulse trains from microelectrodes and the brain patches from functional magnetic resonance imaging (fMRI) to the concerns of psychiatrists, philosophers, theologians, jurists, politicians, estheticians and advertisers. In order to make the bridges neurodynamicists must show how small-scale entities self-organize through forming large-scale entities and transforming and modulating themselves in the circular process. The requisite interactions, variously termed circular causality or feedback whether recurrent or reentrant, occur through serial stages across synaptic connections and non-synaptic channels [Freeman, 2005b] that form chains and both forward and feedback loops. These multi-level dynamic interrelations are schematized by the topological networks of K-sets [Freeman, 1975; Kozma, Freeman and Erdi, 2003].

A well-understood example of serial transformations across forms and scales is provided by the nerve-muscle preparation. The firing rates of axons (cellular events in electrochemical and magnetic energy) are related to the rates of transmitter release at synapses (molecular events in chemical energy), and these are related to the amplitudes of membrane and metabolic potentials of muscle cells (organelle events) and to the strengths of muscular contractions (system events in mechanical energy). A more sophisticated preparation is provided by a sensory system in an anesthetized subject. A stimulus to a receptor activates serially a molecular deformation, a cascading biochemical reaction, a generator potential, a train of action potentials transmitted to the brain, a release of packets of a chemical transmitter, and an activation of synaptic potentials in secondary neurons at a relay in a pathway to cortex. A tertiary neuron, usually thalamic, drives cortical neurons by further chains of chemoelectric transformations, culminating in frontal and parietal activity patterns that ultimately have social significance.

In an awake subject engaged with the environment those driven cortical neurons, even before stimulation, are already self-organized and active through intracortical and extracortical feedback loops. Small numbers of neurons form networks; tens of thousands of neurons form populations; hundreds of millions form modules. The excitatory interactions among neurons support the formation of continually evolving spatial patterns of cortical activity. The inhibitory interactions sharpen and bound those patterns. The interactions among excitatory and inhibitory neurons generate oscillations loosely called brain waves. Spatiotemporal patterns emerge of axonal, synaptic, and dendritic activity in the forms of trains of action potentials, local field potentials (LFP, EEG, MEG), event-related potentials (ERP), and varying rates of dissipation of metabolic energy that demand increased blood flow, from which enhanced activity is deduced. Focused responding to stimuli that subjects have learned to discriminate is accompanied by excitation of cortical neurons singly (feature detectors, cardinal cells, synfire chains, Hebbian networks), in populations (oscillatory brain waves with high vs. low amplitude modulations), and in modules (increases in regional blood flow to meet neural metabolic requirements).

At this point we encounter a major epistemological problem. The patterns of neural activity, which we correlate with conditioned stimuli and behaviors, feed on diverse forms of energy. Observers measure the various energy forms and express their quantities in numbers. The diversity of forms and scales is surmounted by treating the patterns in the numbers as information. The sequential transformations of the information are described with equations from information theory, and the measured spatial patterns, temporal oscillations and transformations

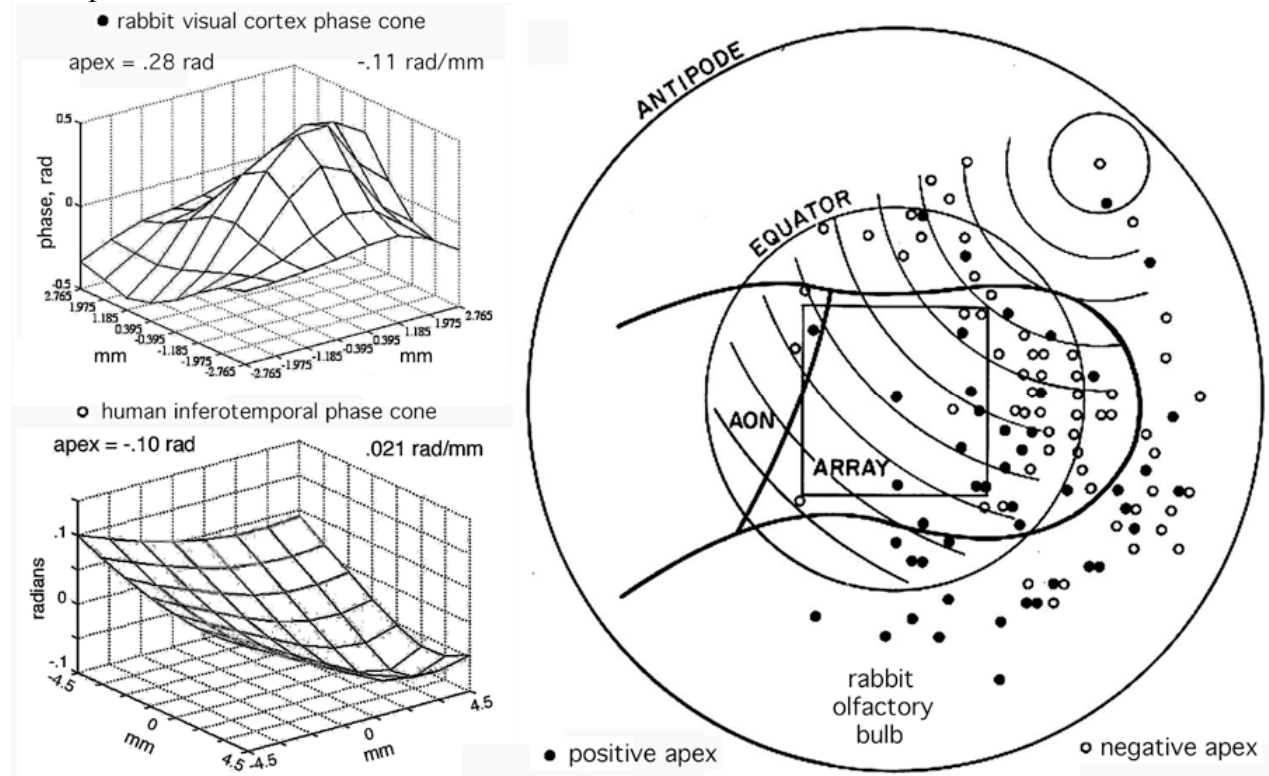
are simulated by solving the equations. These numerical sequences and models provide the backbone of our knowledge about brain functions underlying consciousness. The equations serve to make models of “information processing”, which has become not only a prime method of discovery but also the leading metaphor for describing brain functions in contemporary neuroscience.

It is important to recognize, as in the case of mathematics, that the information is in the dynamic systems models and not in the brain activity that it models. The reason is that brains create, store, retrieve and utilize knowledge from experience, but the knowledge of each subject is unique to that subject, and it is highly resistant to description in terms of information [Bartlett, 1932; Lucky, 1989]. Some of the information that investigators define and deliver to sense organs is certainly incorporated into the knowledge of the subject, but the identity of the information is not preserved or measured, as it can be in a model of the perceptual process. When the model is confused with what it represents, investigators encounter the symbol grounding problem [Harnad, 1999], which has plagued artificial intelligence for half a century: how is a representation in the brain connected with what it represents in the world? For this reason representational and information-processing models fail, and alternative approaches must be explored. The search for alternatives is done by stepping back to broaden one’s point of view.

### **3. Comparison of the reflex arc and the action-perception cycle**

An experimental subject engaged with the environment in a task forms a dynamical system in the form of a circular process that incorporates both subject and object at all levels simultaneously from subatomic to social [Pribram, 1991; Jibu et al., 1996; Chapline, 1999]. The dynamics is analyzed by entering the cycle at either of two starting points: the reflex arc begins outside the brain, and the action-perception cycle begins inside the brain. Each conception has advantages and limitations, so they are complementary. Each stems from a different paradigm, so they are incompatible. The reflex arc is conceived by neuroscientists in Newtonian terms of point-to-point transmission of intensive trains of action potentials from identified neurons having high impact on selected target neurons at the synapses. The oscillations manifesting the impacts have fixed frequencies at zero phase lag [Engel et al., 1991; Schillen and König, 1994; Melloni et al., 2007], which is compatible only with stationarity and instantaneous action-at-a-distance. As with point mass, the energy (firing rate) is positive-valued. The intensities index the probability that a given signal is present [Barlow, 1972]. Contrastingly the action-perception arc is conceived by neuroscientists in terms of Maxwellian fields [Köhler, 1940; Pribram, 1991; John, 2001; Tononi and Edelman, 2000] of low-density activity that is based in the effectively continuous distributions of synaptic energy in populations with billions of synapses/mm<sup>3</sup> [Freeman, 1975, 2000]. The field energy is everywhere, not just at the axon terminals as postulated in a discrete network. Transmission in the establishment of co-active domains is not instantaneous action-at-a-distance but involves propagation delays, which are most clearly seen in the radially symmetric spatial patterns of phase having the form of right cones (Fig. 1) that characterize the oscillations of wave packets [“phase cones”, Freeman, 2004]. The energy values that characterize the spatial patterns are bivalent; low or zero values are just as important as high values for identification and classification, because patterns require black and gray as well as white. This contrast in 21<sup>st</sup> century neuroscience resembles that in 19<sup>th</sup> century physics between Newtonian interpretations of electric and magnetic forces in terms of point charges *vs.* the fields of Faraday and Maxwell

[Barrett, 2000, 2001; Arianrhod, 2005]. Then and now the contrasting views are polar opposites; neither view can be used to critique the other, because the divergence begins with the design of the experiments that are needed to collect the raw data to test them [Kuhn, 1962].



**Fig.1. Left:** examples of phase cones from neocortical electrocorticogram (ECoG, which is EEG recorded directly from cortical surfaces) of human [Freeman et al., 2006] and rabbit [Freeman, 2004b]. **Right:** outline of rabbit bulb with square array superimposed on the opened spherical surface. The arcs show a representative phase cone; the dark symbols • show the locations of positive apices (“explosion”); the light symbols ◦ show negative apices (“implosion”) [Freeman and Baird, 1987]. The phase gradients of phase cones are measured in radians/mm. Biologically the gradients are determined by the ratio of the frequency of the shared oscillation in radians/s to the conduction velocities of axons running parallel to the cortical surface in m/s. The phase patterns and the random variation in sign at the apex from each frame to the next can only be explained by field theory. From Freeman [2007].

The activity in the reflex arc is initiated by an investigator who selects a sensory modality and gives a stimulus with information content that is measured in its features and intensities. The electrochemical responses to the stimulus are measured serially in the sensory receptors, the ascending pathways to cortex, and the hierarchy of cortical networks and modules, for example,  $V1 > V2 > V3 > V4$ . The investigator selects rapidly firing neurons that provide high-density information in small numbers of neurons. The measurements provide the basis for seeking the information that was delivered in the stimulus and calculating the transformations by which that information flows through the brain. The transformations support deductions on how the information is processed, extracted, stored in memory, retrieved, compared with new information, and used to make decisions, select responses, and implement them by movements of the body into the environment, thereby closing the cycle from which the stimulus came. The success of the models is evaluated by calculating deviations between the measured observations and the simulations derived by solving the equations. This approach is well suited for the design,

execution and interpretation of experiments in stimulus-response determinism using the behaviorist tools of schedules of reinforcement [Ferster and Skinner, 1957]. However, the reflex arc cannot describe brain processes of intending goals, planning actions, predicting sensory consequences, attending to input, and creating knowledge by generalizing and abstracting, because as already stated those processes are knowledge-based, not information-based. From a broader perspective the goal of modeling reflex behavior is in the mind of the investigator: to control the subjects' behaviors by the systematic use of reward and punishment. The intentional cycle, of which the conventional reflex arc is one part, begins with the intention of the investigator, extends through the experimental subject, and is closed with the evaluation by the investigator of the conditioned response to the conditioned stimulus, as that stimulus is conceived by the investigator and not as it is perceived by the subject. Hence the reflex model can be subsumed into the action-perception model, but not the reverse.

The activity in the action-perception cycle of Piaget [1930] and Merleau-Ponty [1942] begins with a macroscopic state in the brain that embodies a goal. It emerges in the brain by extrapolation from recent and current input that is embedded in the context of the knowledge base. This predictive state implicitly contains nested mesoscopic activity patterns, which are constructed in corticostriatal and corticocerebellar modules [Houk, 2005], and which mediate the control of the body movements by the motor systems that the macroscopic state predicts may satisfy extant needs. The motor systems transmit to the brain stem and spinal cord the microscopic command patterns of action potentials that implement specific body movements of approach (e. g., grasping) or avoidance (e. g., flight). The descending action patterns include controls of the postural, autonomic and neuroendocrine back-ups for the expected action (commonly identified with expressions of emotions). The cortical modules also organize patterns called corollary discharges [Sperry, 1950], CODAM [Taylor, 2003], and efference copies [von Holst and Mittelstaedt, 1950] that are transmitted to the sensory systems. This process, also called prefference [Kay and Freeman, 1998], conveys to sensory cortices the expectations of the probable sensory consequences of the anticipated action. Phenomenologically the expectations may be experienced as states of desire, fear, lust, rage, etc. Biologically the expectations in sensory cortices have the form of selective sensitivities that are described as landscapes of chaotic attractors in brain state space [Viana Di Prisco and Freeman, 1985; Skarda and Freeman, 1987]. Each attractor supports a dynamic memory embodied in a nerve cell assembly that has been shaped by synaptic changes under reinforcement and other forms of learning. Selection of an assembly leads to activation of an attractor and its stored memory, which is manifested in the emergence of a spatial pattern of amplitude modulation (AM) of a carrier wave in the gamma or beta frequency range. As noted in more detail in the next section, the AM patterns lack invariance with respect to conditioned stimuli [Barrie, Freeman and Lenhart, 1996; Ohl, Scheich and Freeman, 2001]; they change with altered reinforcement contingencies or simply with the addition of new conditioned stimuli in serial conditioning [Freeman and Grajski, 1987; Freeman, 2005a]. Therefore, they do not represent stimuli symbolically or otherwise; they express individual knowledge about the stimuli but well below the level of consciousness. Therefore the symbol grounding problem is not encountered.

A basin of attraction, metaphorically resembling a crater on the moon, surrounds each attractor. The basins form a landscape that the sensory cortex holds up to the world containing the set of predicted possible outcomes of an action into the world. Each possible outcome of an act of



observation (such as an odor of food, a predator, a mate, the background, or a novel, unknown stimulus) leads by serial constructions in the forebrain to an appropriate follow-up behavior (approach, escape, orienting, etc.). All attractors are latent prior to an act of observation, upon which only one can be selected. Only one AM pattern can emerge as the outcome of the impact of the sensory volley on the expectant cortex. This outcome may appear to resemble the affordance of J. J. Gibson [1979], but it differs in the following respect. Gibson wrote: "... the affordance, being invariant, is always there to be perceived. An affordance is not bestowed upon an object by a need of an observer and his act of perceiving it. The object offers what it does because of what it is" [p. 139.] In other words the Gibsonian view holds that perceptual information is in the object and is transferred by resonances into the observer. Since there is no limit on the number of observers, each with individual resonances, the information content in the object is unbounded. Contrastingly in the proposed neurodynamic view the knowledge about the utilities of the object is in the attractor landscapes that are unique for each observer, not in the objects under observation.

A goal-oriented action predictably changes the relations of the senses to the environment, as when the eyes move and the visual fields appear to move oppositely. The barrages of sensory-evoked action potentials impact the sensory cortices, destabilize them, and activate their attractor landscapes by phase transitions. The sensory input to each sensory cortex in the several modalities selects one of the basins, and the dynamics converges to the attractor in the basin. The attractor governs the neural interactions that generate an oscillatory field of neural activity called a wave packet [Freeman, 1975]. The mesoscopic wave packet differs from sensory-driven spike trains in two main respects. First, the domain of coherent oscillation in small mammals is very large, typically 15-30 mm in diameter [Freeman, 2004b], which includes and integrates ["binds"] all subdivisions in each primary sensory area. Second, the information in the measurements of the AM pattern that serves for classification with respect to conditioned stimuli and responses is distributed and holographic; no one channel of EEG has more or less value than any other, whether the amplitude of oscillation is high, low or zero. Therefore, the same content of the wave packet is broadcast by action potentials of pyramidal cells simultaneously to all targets of the hierarchy of modules in the primary sensory areas, just as each fragment of a hologram contains the entire picture though at reduced resolution. The spatial AM patterns of the multiple sensory wave packets signal the same perceptual outcomes of the intentional action to all brain targets about the current status of the body with respect to the environment, signaling which of the expected outcomes has been selected in every modality but without the necessity for consciousness.

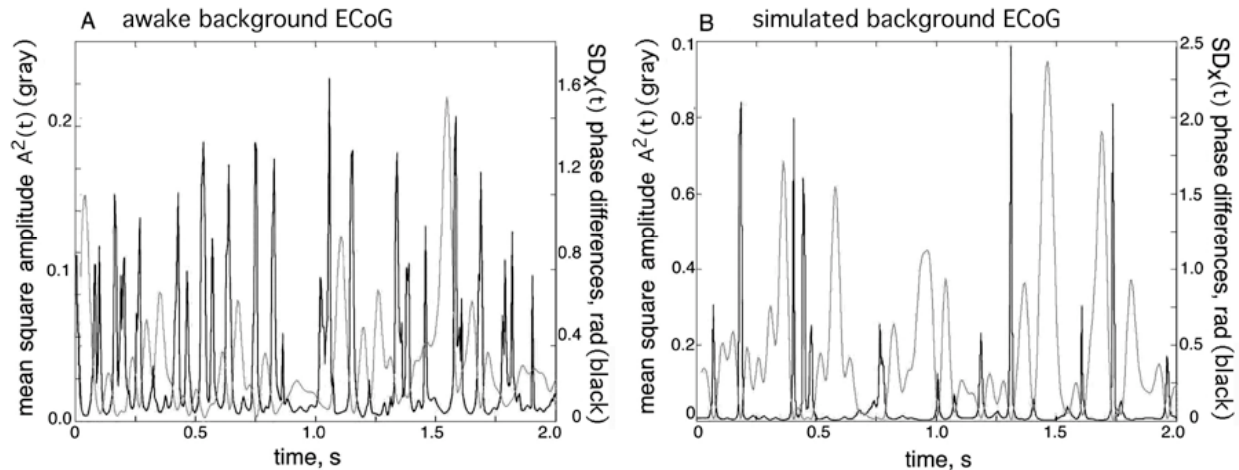
The convergence to an attractor in each cortex performs two operations: it abstracts the input, because convergence is independent of where in the basin of attraction the stimulus receptors happen to place the cortex, and it generalizes to a signal of the category to which a stimulus is assigned, because the attractor is based in the knowledge that has been accumulated by experience, not in the transient stimulus information. This point bears repetition. The stimulus information is unique, ephemeral, material and ultimately unknowable. For example, an odorant excites a specific subset of available receptors, but brains do not know or need to know which receptors. The outcome of convergence to an attractor is an AM pattern that expresses an abstract category that exists only in the brain. To be sure, the AM pattern is material, evanescent, never twice identical but sufficiently reproducible to be correctly classified on repetition over trials.

This distinction in essence is that between matter and mind. The firing of receptors can properly be said to represent a sensory event to the brain, where the action potentials from sensory relays select an attractor that activates a fragment of knowledge. The AM pattern carried by a wave packet does not represent the stimulus to other parts of the brain. It carries the relevant knowledge about the stimulus for integration with wave packets from other sensory cortices, both directly to other sensory and motor cortices and through the limbic system, ultimately to form a unified macroscopic concept as the culmination of an act of perception with closure of the action-perception cycle by extrapolation to prediction of a new future state.

The reflex model originated in the Cartesian metaphor likening the flow of spirit in brain operations to hydrodynamics. Descartes conceived the *sensorium commune* as a complex mirror under central control. The metaphor persists today when brain operations are likened to information processing in computers. The action-perception model originated over 400 years before Descartes in Thomas Aquinas' description of intention ("intendere" from the Latin word for bow string, hence tendon) [Aquinas, 1272] by which brain operations thrust the body into its surround and acquired knowledge by adaptation ("adequatio") to the environment. Goal-oriented behaviors have been described repeatedly in the 20<sup>th</sup> century by pragmatists [Dewey, 1914], developmental psychologists [Piaget, 1930; Köhler, 1940], existentialists [Merleau-Ponty, 1945] and enactionists [Clark, 1996], however without benefit of nonlinear brain dynamics. Only in recent years have developments in dynamics and field theory provided the concepts required to model large-scale neural activity: scale-free dynamics [Breakspear, 2004; Chen and Shi, 2004; Freeman, 2006a, 2006b], circular causality [Haken, 1983], stabilization of brains in pseudo-equilibrium at self-organized criticality [Jensen, 1998], dissipative structures forming by phase transitions far from thermodynamic equilibrium [Prigogine, 1980], anomalous dispersion in the dissemination of phase transitions [Freeman, 2000], extensions of random graph theory into 'neuropercolation' [Kozma et al., 2005], and repetitive destabilization of cortical dynamics in spontaneous symmetry breaking as described in many-body physics [Freeman and Vitiello, 2006, 2007].

#### **4. The construction and expression of knowledge through background activity**

Even the most casual observations of the electric and magnetic fields of the action potentials and dendritic waves from normal brains reveal the spontaneous background activity. Stimulus-response determinists treat this activity as noise and remove it by averaging in order to retrieve event-related potentials (ERP) as signals. Neurodynamicists by close examination of the background activity have extracted and displayed significant mesoscopic structures in the background activity (Fig. 2).



**Fig. 2, A.** This is an example of the analytic signal from array recording of ECoG from a human subject at rest, showing the background activity. When the spatial standard deviation of phase differences,  $SD_X(t)$ , falls to a low value, the mean analytic amplitude,  $A^2(t)$ , increases to a maximum during the period of relatively constant frequency that follows a phase transition [Freeman, 2004b]. **B.** This pattern is simulated by passing *brown noise* ( $1/f^2$ ) through a band pass filter in the gamma range, which shows that the background activity conforms to Rayleigh noise [Freeman, 1975]. Mean analytic amplitude and spatial variance of analytic phase co-vary inversely [Freeman, 2006]. The properties of the background noise and the occurrence of the null spikes at which the analytic phase is undefined can only be explained by field theory. From Freeman [2007]

The individual pulses in trains of action potentials from cortical neurons are uncorrelated within themselves and among others and can be described as a random walk [Kozma et al., 2005] except for the refractory periods. When summed over neighborhoods with  $\sim 10^4$  neurons their combined activity conforms to Brown noise [Schroeder, 1991] with Gaussian amplitude density distributions and spectra of log power vs. log frequency with slopes near  $-2$  [ $1/f^2$ ] but falling to  $-3$  or steeper in slow-wave sleep [Freeman, 2006a]. The activity has been demonstrated to be generated by mutual excitation [positive feedback] among cortical excitatory neurons that is stabilized by the absolute and relative refractory periods [Freeman, 1975] and is therefore governed by a point attractor [Freeman, 2007]. These features carry over into the dendritic potentials through a low pass filter contributed by the passive membrane time constants of dendritic membranes and their cable properties. Negative feedback from inhibitory neurons operates like a band pass filter to introduce oscillations giving the EEG peaks in the spectrum in the beta (12-30 Hz) and gamma (30-80 Hz) ranges. The oscillations recur in bursts separated by intermittent epochs of severe abatement of background noise amplitude (“null spikes”, Fig. 2) that recur at rates in the theta (3-7 Hz) and alpha (7-12 Hz) ranges [Freeman, 2006a]. These null spikes in the background activity are best seen in the analytic signals derived with the Hilbert transform [Freeman, 2006c] applied to electrocorticograms (ECoG) recorded with arrays of electrodes implanted directly onto the cortical surface of brains in animals [Freeman, 2004a,b] and humans [Freeman et al., 2006]. They have also been demonstrated in the scalp EEG in normal subjects [Freeman, et al., 2003; Freeman, Burke and Holmes, 2003]. These null spikes are frequency-specific for the beta and gamma ranges that are determined by the delays in the feedback pathways, local feedback with shorter delays giving gamma [Freeman, 1975] and global feedback with longer delays giving beta.

The amplitudes of the background activity increase with increased arousal and motivation (hunger, fear, etc.). During the bursts between null spikes there emerge spatial patterns of amplitude modulation (AM) of beta-gamma oscillatory wave packets that recur at frequencies in the theta-alpha ranges [Freeman, Burke and Holmes, 2003; Freeman, 2005a]. The AM patterns in the brains of animals are correlated with the actions and inferred perceptions of the animals, but as noted earlier the patterns lack invariance with respect to conditioned stimuli. For example, animals conditioned to discriminate between a reinforced and an unreinforced conditioned stimulus develop three classes of AM patterns, one for each stimulus and one for the background. When the reinforcement is switched, all three AM patterns change slightly but significantly [Freeman and Grajski, 1987]. Therefore, the fields are not fixed representations of the stimuli; they express knowledge about the situations that the animals have learned to expect by interactions with their environments, knowledge that continually evolves with each new sample in changing contexts. The AM patterns of wave packets are created by self-organizing brain dynamics based on synapses among cortical neurons that are modified by prior and on-going learning. The AM fields in each sensory cortex form sequences of stationary states that resemble frames in a cinema [Sacks, 2004]. Each frame is separated from those preceding and following by a phase transition that imposes a discontinuity in cortical dynamics, a discontinuity that appears to be facilitated by the null spike in the background activity. These data show that the cognitively related content of AM patterns is not superimposed on the background, from which it can be retrieved by averaging over trials. The content is created when sensory input during a null spike activates a nerve cell assembly that accesses an attractor, which re-structures the background activity as it returns by imposing its AM pattern [Freeman, 2007]. The transition constitutes the retrieval of knowledge guided by the stimulus, not the processing of information contained in the stimulus.

Two classes of AM pattern have been found in animals trained in classical and operant conditioning paradigms. In each trial early after stimulus onset an AM pattern appears that is modality-specific; its mesoscopic field is localized in the relevant primary sensory area, and the oscillation has a carrier frequency in the gamma range. Later but before the response onset another type of oscillatory macroscopic field appears that is synchronized over all of the primary sensory areas and the entorhinal cortex [Freeman and Rogers, 2003]. The frequency is in the beta range, and all sensory and limbic areas participate in its AM pattern [Freeman and Burke, 2003]. Gamma oscillations seldom occur in prestimulus control epochs, whereas beta oscillations occur with the same probability in prestimulus and poststimulus epochs.

The proposed sequence of events in an action-perception cycle is summarized as follows. The expression of intent to act by initiating a sniff, whisk or saccade is accompanied by an update by corollary discharges of the attractor landscapes in all sensory and motor areas. Each area has its own asynchronous pacing of opportunities for phase transitions in the null spikes in its background activity. The arrival of a corollary discharge may precipitate a macroscopic phase transition that is manifested in a beta burst. The arrival of a volley of action potentials relayed from sensory receptors, when it coincides with a local null spike in the gamma range, achieves the signal-to-noise ratio that is required for the selection of a nerve cell assembly, thereby accessing the corresponding attractor by a mesoscopic phase transition. When the background noise returns, the gamma band contains a wave packet with the AM pattern corresponding to the class to which the stimulus is assigned in each modality. The sensory cortices broadcast their

wave packets to widespread targets; the signals converge by stages to the outer layers of the entorhinal cortex, go through the hippocampal loop, and return to the inner layers of the entorhinal cortex, whereupon the combined signals are sent back to all of the sensory areas. As described above the subsequent beta AM patterns are synchronized across sensory and limbic cortices [Freeman and Rogers, 2003] and are polysensory, because classification is optimal when EEG information from visual, auditory, somatic, olfactory, and entorhinal areas is included, and it is diminished when any of these components is omitted [Freeman and Burke, 2003].

These data indicate that, roughly half a second after stimulus onset, two to three stimulus-related macroscopic cortical AM patterns of synchronized oscillation emerge preceding the onset of a response to a stimulus, each lasting on the order of a tenth of a second. In cats and rabbits the correlation distance suffices to extend across the entire hemisphere [Freeman, 2004a]; in human scalp EEG the correlation distance occasionally reaches the length of the recording array [189 mm] for EEG [Freeman, Burke and Holmes, 2003] and an estimated 225 mm for MEG [Bassett et al., 2006]. It is a subset of these macroscopic patterns that I propose as a neural correlate of consciousness. What is not yet known is whether the large domains form either a mosaic of discrete patches interacting as a network, in accord with a Newtonian model, or a continuum as in a Faraday-Maxwell field. Wolfgang Köhler [1940] was quite explicit about this: "Our present knowledge of human perception leaves no doubt as to the general form of any theory which is to do justice to such knowledge: a theory of perception must be a field theory. By this we mean that the neural functions and processes with which the perceptual facts are associated in each case are located in a continuous medium" p 55]. Regrettably Köhler identified his perceptual field with the epiphenomenal electric field of the EEG, of which the Coulomb forces are much too weak to synchronize the observed oscillations in wave packets [Freeman and Baird, 1989]. This subsidiary hypothesis was easily disproved by Sperry [1958] and Pribram [1971], with the unfortunate outcome that field hypotheses were largely abandoned by mainstream neuroscientists.

## 5. Deducing some properties of consciousness from nonlinear brain dynamics

Since I cannot demonstrate what my subjects experience or even whether they are conscious, I describe consciousness as existing in the state of engagement with the environment that may be experienced by animals and pre-lingual children who cannot speak about it. This state that one can attribute to engaged subjects can be behaviorally distinguished from states on the one hand of self-awareness, introspection, or 'spectatoring' and on the other hand of dozing, dreaming, deep anesthesia, and *absence* in partial complex seizure. I define three neural correlates of the designated state in animals: arousal, intention, and attention. The degree of arousal (conceived by psychologists in terms of motivation, drive or desire) can be estimated by the mean level of self-stabilized background spike firing and dendritic activity [Freeman, 2007], for example, by measuring the root mean square amplitude of gamma activity from the olfactory cortex [Freeman, 1960, 1975]. The degree of intention (often conflated by psychologists with motivation) can be estimated by the *a priori* likelihood that any one of a list of designated responses will occur following delivery of a learned stimulus, and by an index,  $H_c(t)$ , defined as pragmatic information [Freeman, 2004a,b] that is calculated from the analytic signal of neocortical EEG [Freeman, 2005a]. The degree of attention is more problematic, owing to the lack of a commonly accepted neural referent. According to James [1890]: "Everyone knows

what attention is. Focalization, concentration, of consciousness is of its essence. It implies withdrawal from some things in order to deal effectively with others, and is a condition which has a real opposite in the confused, dazed, scatterbrained state." A more contemporary dictionary definition of attention is "An adjustment of the sense organs and of the organism generally, preparatory to actual observation of something; a focusing of conscious activity on anything; as, attention to a problem; the act or fact of bringing something into clear awareness; ..." [Webster, 2nd ed., unabridged, 1949]. In Newtonian models the degree of attention can be assessed by the synchronization of firing of tuned neurons [Mehta, Ulbert and Schroeder, 2000; Posner and Dehaene, 1994]. In field models the neurally based measure of the level of attention may be indexed by the degree complexity of attractor landscapes in the sensory cortices that serve to predict expected classes of sensory input, as measured by multivariate classification algorithms applied to AM patterns [Viana Di Prisco, 1985; Barrie, Freeman and Lenhart, 1996; Kay and Freeman, 1998; Ohl, Scheich and Freeman, 2001; Kozma and Freeman, 2002; Freeman, 2005a]. The landscapes are based in nerve cell assemblies formed in cortical neuropil during cumulative learning. The precise numbers and locations of modified synapses cannot be directly observed or measured. Their existence is demonstrated by the short-latency emergence of gamma AM patterns following receipt by subjects of relevant conditioned stimuli.

At what stage of the action-perception cycle might consciousness emerge? While involvement of the hippocampal formation is not wholly necessary for consciousness in the limited sense here intended, it is necessary for the accumulation of episodic memories into the recollection of a lifetime [Squires, 1990], and since such memories typically are polymodal, and since human subjects require roughly half a second before reporting awareness of a stimulus [Libet, 1994], a candidate for the neural correlate of consciousness on perceiving a stimulus is one or more of the beta macroscopic events recorded late in the stimulus-response interval. Adequate EEG data from human experiments in self-awareness are not yet on hand. Which in a sequence of beta frames the correlate might be identified with is not clear; that cannot be determined from tests with non-human animals, because they lack speech. The further problem is that turbulent streams of multiple overlapping spatial patterns of phase and amplitude in beta oscillations flow equally before and after the arrival of an expected stimulus. The durations of the patterns give power-law distributions with means and variances that change with the duration of the measuring window [Freeman, 2004b; Freeman et al., 2006]. The patterns resemble bubbles in a pan of boiling water that maintain its critical temperature, and the avalanches in a sand pile that maintain its critical angle. In cortex this on-going activity manifests the maintenance by cortex of its conditionally stable level of activity at self-organized criticality, for which the self-maintained critical variable is the self-regulated mean level of cortical firing [Freeman, 2007]. The deviations from the power-law distributions of spectral energy in subjects at rest, which manifests endogenous noise, is the emergence in the cortices of engaged subjects of local peaks of spectral energy reflecting oscillatory bursts carrying spatial AM patterns that last longer than expected for noise and therefore reveal signals [Freeman, 2005]. And among these self-organized bubbles are synchronized oscillations in the beta and possibly gamma ranges that rapidly form and dissolve with correlation distances at least 189 mm [Freeman, Burke and Holmes, 2003] and 225 mm [Bassett et al., 2006], which may be requisite for the apparent unity of consciousness.

This excess of long-lasting AM patterns having 3-5 cycles of the carrier frequency includes the AM patterns that are classifiable with respect to conditioned stimuli. They comprise a small

proportion of the concomitant AM patterns, which might include not only percepts of stimuli but also motor commands, corollary discharges, and expectations that are likely to be unconscious or preconscious. In the view from neurodynamics the identity of an individual, the “real person”, “proto-self” [Damasio, 1999] or “global work space” [Baars, 1997] is embodied in the entirety of the brain-body dynamics, not only in the fragments available to introspection. The prime source of self-knowledge and being known by others is observation and inspection of one’s actions, not one’s stated intentions. Voluntary actions might be classed as those relatively few intentional actions that succeed informed reflection without necessarily conforming to its conclusion [Davidson, 1980]; intentional actions lacking this condition are thereby not conscious. EEG evidence [Walter, 1953; Libet, 1994] indicates that voluntary actions are initiated about half a second before awareness of the intent to act, leaving time for veto.

The veto is obviously by intention, which is the mechanism described above for the action-perception cycle. It is unclear what the timing might be for the preconscious perception of an event *vs.* the decision to report the perception *vs.* the awareness of deciding. While in principle the AM patterns of beta wave packets may be accessed through the scalp EEG, the techniques for doing so remain to be developed in human studies. Several experimental findings give reason to expect eventual success. First, intentional actions involve the whole body [Bernstein, 1967], even for constrained actions such as finger-presses, owing in the latter case to active inhibition of all other movements, to anticipatory feedforward set-ups for exteroceptive and proprioceptive feedback, and to the janitorial back-ups in posture, autonomic adaptations and neuroendocrine regulation, so that cortical fields of the relevant macroscopic beta events are likely spread widely and involve the frontal and parietal lobes. Second, the dynamics of neocortex is scale-free [Freeman, 2006b], meaning that the time required for reorganization in a phase transition is independent of the size of the domain of incipient synchrony, so they may be immense compared to the radii of dendritic branches. Third, the spatial resolution of amplitude differences carried by beta-gamma activity fields may approach the dimensions of gyri (1-3 cm) [Freeman et al., 2003], indicating that the most revealing spacing of electrodes (the Nyquist sampling rate) on the scalp might be 3-5 mm, not the 25-50 mm currently in common clinical use. Fourth, the information that contributes to classification is equal on all electrodes in an array; the finding is that no channel is more or less important than any other; the implication is that classification improves with the number of electrodes irrespective of location, provided the locations are not moved between samples.

Some further properties that can be deduced from dynamics and field potential data are that consciousness is reactive and judgmental of the results of intentional action late in the action-perception cycle, not enactive in the initiation of an act: “What have I done?” rather than “What shall I do?” In this perspective its role is to defer action pending closure of the search of knowledge from experience prior to an intentional action. Judgment consists in constructing and contrasting possible courses of action given the environmental circumstances of the moment. When a conclusion is reached on what is best done, action ensues, but all too often the action initiated is not that considered as optimal but may be detrimental. Davidson [1980] described this type of action as ‘incontinent’; it is clear evidence that the conscious state, whatever it might be, is not the same as the neural activity pattern that actually selects the action initiated.

## 6. Conclusion and Summary

While neurodynamics cannot explain consciousness, it does open novel perspectives for discussion, and it offers four predictions of neural correlates of consciousness that follow from a field theory and that cannot be explained by current network theories. To be a field in the sense intended, a cooperative domain must be an embedding continuum that provides energy at every point, as distinct from a network of synchronized nodes such as synapses and trigger zones at which energy is conceived as a point process. The embedding field is apparent in the background activity, which is highly structured by diffuse interactions (Fig. 2). The carrier oscillations must have a spatial structure of analytic phase modulation indicating that cortex is a relativistic medium as distinct from ‘zero lag’ synchrony (Fig. 1). And the neural correlate of a reported experience must be an AM pattern in which highs and lows have equal information, as distinct from a code in which the amount of information is related to the intensity of activity of each neuron in a focus: its frequency or timing of firing viewed a point process.

From these considerations I propose that consciousness can be defined as a field of force that is centered in a brain and that operates through the body simultaneously into all levels of the surround from subatomic to social. Awareness is perception of the forces of self and others as in peer pressures and familial forces. Unconsciousness comprises the immense reservoir that is provided by the nonlinear neurodynamics of the neural interactions, and that shapes the contents and structures of the field of force.

We perceive that kind of force in the same way that we perceive all kinds of force — gravitational, electric, magnetic, chemical, thermal, social — through volitional actions of the body and their impacts on our sensory and perceptual systems.

We describe and measure that kind of force in the same way that we measure all kinds of force: indirectly by measurement of the correlates of that force in the patterns of goal-directed bodily motion and acceleration of mass in space and time, i.e., intentional behavior.

This definition is consistent *inter alia* with the views of Aquinas, James, Dewey, Freud, Köhler, Koffka, Lotka, Merleau-Ponty, and with the Chinese conception of Qi. Owing to lack of sufficient data, this definition is at present limited to consciousness in animals, infants, and pre-lingual children. Unlike Whitehead [1938], Penrose [1994] and Chalmers [1996] I do not postulate panpsychism but restrict consciousness to animals having advanced laminated neuropil (cortex), which has evolved three times independently in earth’s history, resulting in the diverse brain structures in highly intelligent species in three phyla: Mollusca (cuttlefish), Arthropoda (honeybees), and Vertebrata (humans).

Brain science takes us beyond our philosophical predecessors into mind science. From measurements of neural correlates of behavior, I deduce the following properties of consciousness from its conception as a field of force:

- Brains hold themselves at criticality, where all frequencies and wavelengths coexist in scale-free fields of neural activity, directing the brain-body system to move unitarily and instantly in any selected direction. This is an up-date and extension of the classic Sherringtonian concept of “the final common path”.
- Discontinuities: The stream of consciousness is not continuous; it is in cinematographic frames formed by endogenous phase transitions that are enabled by the property of criticality.



- Arousal: The neural correlate is the mean firing rate of neurons throughout the cortex, sampled through its control parameter, the strength of dendritic current manifested in the brain waves. Modeling with differential equations or equivalent is required.
- Attention: The neural correlate is the set of attractor landscapes in the phase space of the primary sensory cortices. Again, modeling with nonlinear equations is required.
- Intention: The neural correlate is the identification of spatiotemporal patterns of beta and gamma activity in cinematographic frames correlated with goal-directed behaviors. The tools of multivariate statistics, engineering mathematics, and physics are required.
- The role of consciousness is deferral of future action pending closure of evaluation of the information acquired by prior intentional action: stop and think.

The aim of consciousness studies should be a set of master equations that relate material and psychosocial state variables, comparable to the equations of Newton, Maxwell and Einstein, but going beyond the physical aspects of the universe and unifying it with the human aspects of the universe. Such a mind theory is needed to provide a scientific foundation for the behavioral sciences, including psychiatry, as envisioned by Freud (1895).

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