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Three Centuries of Category Errors in Studies of the Neural Basis of Consciousness and Intentionality

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Abstract—*Recent interest in consciousness and the mind–brain problem has been fueled by technological advances in brain imaging and computer modeling in artificial intelligence: can machines be conscious? The machine metaphor originated in Cartesian ''reflections'' and culminated in 19th century reflexology modeled on Newtonian optics. It replaced the Aquinian view of mind, which was focused on the emergence of intentionality within the body, with control of output by input through brain dynamics. The state variables for neural activity were identified successively with animal spirits, élan vital, electricity, energy, information, and, most recently, Heisenbergian potentia. The source of dynamic structure in brains was conceived to lie outside brains in genetic and environmental determinism. An alternative view has grown in the 20th century from roots in American Pragmatists, particularly John Dewey, and European philosophers, particularly Heidegger and Piaget, by which brains are intrinsically unstable and continually create themselves. This view has new support from neurobiological studies in properties of self-organizing nonlinear dynamic systems. Intentional behavior can only be understood in relation to the chaotic patterns of neural activity that produce it. The machine metaphor remains, but the machine is seen as self-determining. © 1997 Elsevier Science Ltd.*

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1. INTRODUCTION

Studies of the neural basis of consciousness have recurred in the biomedical literature for 2500 years, beginning with Hippocrates:

> One ought to know that on the one hand pleasure, joy, laughter, and games, and on the other, grief, sorrow, discontent, and dissatisfaction arise only from [the brain]. It is especially by it that we think, comprehend, see, and hear, that we distinguish the ugly from the beautiful, the bad from the good, the agreeable from the disagreeable... Furthermore, it is by [the brain] that we are mad, that we rave, that fears and terrors assail us—be it by night or by day—dreams, untimely errors, groundless anxiety, blunders, awkwardness, want of experience. We are affected by all these things when the brain is not healthy, that is, when it is too hot or too cold, too moist or too dry, or when it has experienced some other unnatural injury to which it is not accustomed (Clarke and O'Malley, 1968, pp. 4–5).

The last strong outpouring from biologists came 40 years ago following the discovery of the midbrain and thalamic reticular activating systems and their roles in arousal and attention (Adrian et al., 1954). In the past two decades, contributions have come from researchers in brain imaging, psychology, psychiatry, neurology, philosophy, mathematics, physics, computer science, and artificial intelligence. As a result, a shift of immense magnitude is taking place in our understanding of ourselves, but none of us has the perspective yet to grasp its nature and significance. The limitation stems from the circumstance that the bulk of new data has been obtained within the confines of the machine metaphor for mind/brain function. This essay aims to explore the origin of that metaphor from what preceded it, and to indicate a new approach to mind/brain studies.

2. THE ORIGIN OF BRAIN DYNAMICS IN THE MACHINE METAPHOR

Behaviorists have a long history of using natural science

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to explain what they can observe among animals and their fellow humans. The Greeks invented a chemistry of the soul, in which the four elements (air, earth, fire and water) combined to make the four humors of the body (phlegm, blood, black bile and yellow bile), whence the Hippocratic temperaments: phlegmatic, sanguine, melancholic and choleric. Aristotle applied his physics to conceive the brain as a radiator to cool the blood. The foundation for a dynamics of behavior was laid by Descartes, who proposed that the brain operated as a pump for fluids termed ‘‘animal spirits’’, which flowed through the ventricles from the brain into the spinal cord and out into the muscles. The valves such as the pineal gland were controlled by the soul in humans but were automatic in animals, they being soulless machines.

The seminal importance of this formulation can be seen from the following standpoint. In a dynamical system some material thing moves with time. Since Newton and Leibniz the preferred description has been a differential equation, which relates time as it elapses independently (in either direction) to something in the system that is changing. That ‘‘something’’ is the state of the system, and its descriptor is a ‘‘state variable’’. It is essential to measure accurately both the time lapse and the state variable, because the equation gives the relation between the numbers that represent time and the state variables. In Cartesian studies of the brain, the state variable would have represented the flow of animal spirits, had the equations been written. No one did this. The difficulty was that there was no way to measure the flow of animal spirits through the nerves. Descartes postulated that the muscles were shortened by being pumped full of the fluid like a balloon. Physiologists tested this prediction by inventing the plethysmograph to measure the volume of muscle before and during contraction. There was no increase but, in fact, a slight decrease owing to expulsion of blood from the veins by muscle contraction, which showed that animal spirits had no volume to measure. Hence animal spirits could not be represented by a string of numbers in a model. This is an example of what Gilbert Ryle (1949) called a category error, in this case the assignment of the physical property of volume to an immaterial entity. There were more such errors to follow.

Late in the 18th century a Bohemian ophthalmologist named Giri Prochaska made a remarkable discovery. Until that time most scientists had assumed that the brain was a source of animal spirits. Prochaska observed the behavior of newborn anencephalics and found their behavior to be entirely normal. As we now know the human cerebrum is essentially nonfunctional at birth. His findings led him to propose that sensory receptors are the source of animal spirits, which are released by the action of stimuli from the environment. He then drew explicitly on Newtonian optics to formulate a theory of reflex action:

> The reflection of sensory impressions into motor...is not performed solely according to physical laws...but follows special laws inscribed, as it were, by nature on the medullary pulp... The general law...is that of our preservation: so that certain motor impressions may follow external impressions about to harm our body and produce movements aimed at warding off and removing the harm...or sensory impressions about to be favorable to us, and produce movement tending to preserve that pleasant condition longer (Prochaska, 1784, p. 116).

The brain was seen as complex but passive mirror. ‘‘Reflections’’ became reflexes. Three decades later Prochaska made another category error in identifying his ‘‘sensory impressions’’ with electricity newly discovered by Galvani and Volta. This hypothesis was disputed by Carlo Matteucci, who maintained that nerves carried spiritual force, that came to be identified with ‘‘élan vital’’.

3. NERVE ENERGY REPLACES VIS NERVORUM

The hegemony of physics was re-established by the Young Turks. Du Bois-Reymond discovered the injury current and the ‘‘negative variation’’ (the nerve action potential). Helmholtz measured its conduction velocity. Sechenov developed an animal model for anencephaly by pithing a frog to study reflexes. The centerpiece of this antivitalist movement was the experimental demonstration of the First Law of Thermodynamics, the conservation of energy. In the grandest category error of them all, the animal spirits and élan vital were replaced with nerve forces and nerve energies, which flowed from the environment through the sensory receptors into the brain and back out again through the muscles, after being stored in nerve cells and then ‘‘liberated’’. The new doctrine was announced by Herbert Spencer (1863, p. 109):

> [It is]...an unquestionable truth that, at any moment, the existing quantity of liberated nerve-force, which in an inscrutable way produces in us the state we call feeling, must expend itself in some direction—must generate an equivalent manifestation of force somewhere... [A]n overflow of nerve-force, undirected by any motive, will manifestly take the most habitual routes; and, if these do not suffice, will next overflow into the less habitual ones.

Charles Darwin (1872, p. 70), continued:

> This involuntary transmission of nerve force may or may not be accompanied by consciousness. Why the irritation of nerve-cells should generate or liberate nerve force is not known; but that this is the case seems to be the conclusion arrived at by all the greatest physiologists such as Mueller, Virchow and Bernard, and so on.

The application of Newtonian dynamics was also explicit in the writings of J. Hughlings Jackson (1884, pp. 42–44):

> ...we speak of the dynamics of the nervous system... A normal discharge starting in some elements of the highest centres overcomes the resistance of some of the middle, next the resistance of some of the lowest centers, and the muscles are moved... A fit of epilepsy is an excessive caricature of normal physiological processes during what is called a voluntary action... We have, in the case of ''discharging lesions,'' to consider not only the quantity of energy liberated, but the rate of its liberation... *Resistances* will be considered later.

A note in Jackson's handwriting was later found in the margin of this text: ''No more of this was published.'' It may have already become clear that while nerve tissue did have electrical resistance, the barrier to the flow of ''nerve energy'' was not so simple. The principle of the conservation of momentum was also used by Sigmund Freud as a foundation for his project of a scientific psychology, in which he confused his neuronic inertia with dendritic current:

> This line of approach is derived directly from pathological clinical observations, especially those concerned with excessively intense ideas... These occur in hysteria and obsessional neurosis, where, as we shall see, the quantitative characteristic emerges more plainly than in the normal... What I have in mind is the principle of neuronic inertia, which asserts that neurones tend to divest themselves of quantity (Q)... We arrive at the idea of a ''cathected'' neurone (N) filled with a certain quantity... The principle of inertia finds expression in the hypothesis of a current, passing from the cell-processes or dendrites to the axone... The secondary function [memory] is made possible by supposing that there are resistances which oppose discharge...in the contacts [between the neurones] which thus function as barriers. The hypothesis of ''contact-barriers'' is fruitful in many directions (Freud, 1895, pp. 356–359).

Two years later these barriers were named by Michael Foster and Sir Charles Sherrington:

> Such a special connection of one nerve-cell with another might be called a synapsis (Foster and Sherrington, 1897, p. 929).

Some four decades later the hypothesis of synaptic resistance was undermined by Otto Loewi's discovery of chemical neurotransmission, though it persists in more realistic treatments of electrical synapses, in which it refers to electrical current and not to nerve energy.

Another physical principle, the field of potential that was developed by Michael Faraday to explain electrical and magnetic forces, was coopted by Gestalt psychologists to explain their data from studies in perception:

> ...let us think of the physiological processes not as molecular, but as molar phenomena... Their molar properties will be the same as those of the conscious processes which they are supposed to underlie (Koffka, 1935, p. 57).

> The task of psychology...is the study of behavior in its causal connection to the psychophysical field (Koffka, 1935, p. 67).

The environment was conceived as a source of nerve energy, which flowed through the sensory receptors into the brain with striking motivational consequences:

> ...things in our environment tell us what to do with them... Their doing so indicates a field of force between these objects and our Egos...which...leads to action. ...A handle wants to be turned, ...chocolate wants to be eaten, ... (Koffka, 1935, p. 353).

One of the principle architects of Gestalt psychology, Wolfgang Köhler, presented meticulous studies of interactive phenomena in perception:

> 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 (Köhler, 1940, p. 55).

He pressed further into physics by identifying the perceptual fields with the electrical fields of the newly discovered electroencephalogram. This hypothesis was identical in form to the category error of Prochaska. It was quickly disproved by Roger Sperry (1958), who placed strips of mica and silver needles in the visual cortex of trained cats and monkeys and showed that the resulting distortions in electrical fields had negligible effects on behaviors involving visual perception. Unfortunately, for this and other reasons, the body of Gestalt theory was discredited among neurobiologists.

With continuing advances in the analysis of anatomical pathways in the cerebrum it became increasingly obvious that the concept of mass flow of energy made no sense. According to Lashley (1942, pp. 302–306):

> Generalization [stimulus equivalence] is one of the primitive basic functions of organized nervous tissue. ...Here is the dilemma. Nerve impulses are transmitted...from cell to cell through definite intercellular connections. Yet all behavior seems to be determined by masses of excitation... What sort of nervous organization might be capable of responding to a pattern of excitation without limited specialized paths of conduction? The problem is almost universal in the activities of the nervous system.

He had already noted the difficulty of finding useful concepts:

> ...expressions like mass action, stress patterns, dynamic effects, melodies of movement, vigilance, or nervous energy [are] all highly metaphorical and unproductive of experimental problems (Lashley, 1929, p. 254).

Yet he continued to borrow from the physical sciences fuzzy concepts such as ‘‘reverberatory circuits’’, ‘‘equivalent nervous connections’’, ‘‘systems of space coordinates’’, ‘‘wave interference patterns’’, ‘‘tuned resonating circuits’’, etc. (Lashley, 1950).

4. INFORMATION REPLACES NERVE ENERGY

The repeated failure of the energy metaphor opened the way for a new approach that came from the communication sciences. Basing their work on Golgi analyses of the entorhinal cortex by Rafael Lorente de Nó (1934), Warren McCulloch and Walter Pitts introduced the concept of nerve cells operating as binary switches in neural networks to compute Boolean algebra. John von Neumann used this concept to develop programmable digital computers. Shannon and Weaver developed the theory of information by *divorcing it from meaning*. This led to the replacement of ‘‘energy’’ by ‘‘information’’ as a descriptor of neural activity. Information and energy are both conceived as flows from environmental ‘‘sources’’. They are transduced through sensory systems, transmitted by axonal tracts as channels, carried by action potentials (bits), transformed (processed) in brains by synapses working as binary switches, stored as fixed patterns (representations), recalled by read-out under constraints of finite channel capacities and entropic losses, like the content addressable memories in computers, and matched or cross-correlated with new input patterns.

Information metaphors are found at four levels. At the level of nerve cells the single neuron is seen as generating a pulse train to represent a meaning corresponding to the Logical Positivist element of a word or an object, such as a grandmother. The frequency of the train represents the probability that the object is present (Barlow, 1972). Members of a distributed collection of neurons that symbolize the same object are called ‘‘cardinal cells’’, deriving from a College of Cardinals running the brain, as distinct from the pontifical cell decried by Sherrington (1940, pp. 177–178):

> In the great head end which has been mostly darkness spring up myriads of twinkling stationary lights and myriads of trains of moving lights of many different directions... The brain is waking and with it the mind is returning. It is as if the Milky Way entered upon some cosmic dance. Swiftly the head-mass becomes an enchanted loom where millions of flashing shuttles weave a dissolving pattern though never an abiding one; a shifting harmony of subpatterns.

An alternative formulation holds a neuron to be a ‘‘feature detector’’ by virtue of its afferent synaptic connections, which are modified and adaptively shaped by prior learning. A collection of feature detectors defines an object when their pulse trains become synchronized, a proposed solution to ‘‘the binding problem’’ (Milner, 1974; von der Malsburg, 1983) of getting feature detectors to work together. Large arrays of such neurons form Hebbian nerve cell assemblies and neural networks, which provide the basis for neurocomputation or computational neural science. A well-known example is the tensor system for coordination of hand movements under visual guidance by cerebellar circuitry developed by Pellionisz and Llinás and reviewed by Churchland (1986).

At the behavioral level and among successors of the Gestalt school, most notable is J.J. Gibson, in whose work the ‘‘affordances’’ denote information that flows into the brain from outside the body through exteroceptors and from inside the body through the proprioceptors:

> ...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 it is what it is. ...But this does not in the least imply separate realms of consciousness and matter, a psychophysical dualism. It says only that the information to specify the utilities of the environment is accompanied by information to specify the observer himself... [E]xteroception is accompanied by proprioception...to perceive is to coperceive oneself (Gibson, 1979, p. 139).

Information is delivered into resonant circuits in the brain, and it flows out again as ‘‘effectivities’’ from muscles and glands in object-oriented actions. According to Shaw et al. (1990, pp. 586–587):

> Gibson, like Tolman, would disagree with [the view of] Skinner...that the organism is merely a ‘‘through-put system’’. For Tolman, cognition can embellish the stimulus, while for Gibson, stimulus must be informative about the environment in ways that a stimulus, as a physiological ‘‘goad;’’ or a reflexive ‘‘force’’, could never be. They both endow [the organism] with a complex interior—which Tolman cites as the residence of cognitive functions and Gibson as the seat of a tunable (not necessarily linear) information detection operator which resonates to qualitative environmental properties (i.e. affordances). For Gibson, the environment that surrounds an organism is real and objective for each given organism.

The metaphorical ‘‘resonance’’ is reminiscent of Karl Lashley’s ‘‘tuned resonating circuits’’. It is metaphorical, because no physiological embodiment has yet been demonstrated. The difficulties of pursuing this line of theory have been well formulated by Shaw and his colleagues. For example, the infinite complexity of ‘‘objects’’ in unstructured environments is treated by converting objects to numbers:

> ...by following Cantor’s fractalization rule, we have a way to rescale continuous geometric objects so that their dimensionality is reduced. Moreover, by following it with finite recursion, we find that there are objects without integer dimensions... These are Mandelbrot’s fractals... (Shaw and Kinsella-Shaw, 1988, pp. 197–198).

They resolve the paradox that is inherent in combining past experiences and future goals by postulating a dual

Minkowski space with the two cones of past and future melded at the apex of the present, and they propose:

> ...an environment of information which dynamically links a socially invariant exterior with both a biologically invariant interior frame, on the one hand, and with a still more exterior physically invariant frame on the other. That psychological inverse dynamics must couple energy with information across a frame exterior (observable) to one and interior (controllable) to the other, and vice-versa, defines what is meant by an ecological map (Shaw et al., 1990, p. 587).

Their proposed exploration of the role of intentionality in purposive behavior by ecological psychology will depend heavily on the development of graphical computer displays for the three levels of maps and the derivation of equations to describe the operations required for transfer of information between them. At present, their efforts are remote from direct observations made on the dynamics of brains.

At the subneuronal level, the discovery of DNA as the basis for transmission of genetic information has also stimulated search for stores of experiential information in the form of ''memories'' in RNA molecules as well as synapses. The search for the ''molecular alphabet'' of learning is now among the hottest areas of neurobiological research (Alkon, 1992), although studies of synaptic modification have not yet progressed beyond habituation, facilitation, and simple go/no go reflex arcs. Holger Hyden demonstrated a change in RNA in the brains of rats trained to climb a wire and suggested that it indicated the storage of a procedural memory in the neurons of the vestibular nuclei. This line of thinking culminated in studies by worm runners to transfer the memory of working a T-maze from trained Planarian flatworms to their naive, cannibalistic siblings. After initial success this hypothesis failed in the hands of trained scientists, but it is still being ''replicated'' in high school science fairs annually across the country.

At the submolecular level is a variant of the information hypothesis, in which ''quanta of sentience'' emerge as Heisenbergian potentia from a ''sea of universal consciousness'' (Herbert, 1993, p. 26):

> Though materialists agree that mind (defined as ''inner experience'') is no more than a particular motion of matter, they differ concerning how complex matter's movement must be actually to produce a noticeable sensation, to generate what might be called a ''quantum of sentience''...analogous to physicist Max Planck's famous quantum of action.

The main hope that drives these investigations is for discovery of new laws of physics (Penrose, 1989), which will explain such paranormal phenomena as teleportation, precognition, distance viewing, and related forms of extrasensory perception (Herbert, 1993, p. 248):

> Most quantum models of consciousness are similar to Crookes's coherer proposal in that they consider the synapse to be a sensitive receiver of mental messages that originate outside the brain. The main difference between the coherer model of mind and quantum consciousness models is that...-mind is somehow resident in Heisenberg's quantum potentia rather than in electromagnetic ether.

Criticisms that brains, neurons, organelles and receptor molecules are neither small enough nor cold enough to afford quantum coherence have been met with the rejoinder that superconductivity is a macroscopic state of coherence that has already been achieved at temperatures approaching Siberian winter nights, and that it may soon be found also at normal brain temperatures. Less easily handled have been the criticisms that, for all its power in chemistry, quantum mechanics is a linear, first-order, discrete approximation for protons, that it is even inadequate to describe the collapse of the wave function, and that it is poorly suited for describing the nonlinear continuous time dynamics displayed by the nervous system at all levels. More to the point, this line of thought is new wine in an old bottle. The same properties are invoked as for energy and information: environmental sources of input, sinks for output, tuned receptors to resonate with selected inputs, and connectionist mechanisms for storage and retrieval. The elemental building blocks (reflexes, action potentials, bits, words, symbols, primitives, and quanta) change with the centuries, but the underlying concepts have been passed whole from one generation to the next.

5. THE UNIQUENESS OF BRAIN FUNCTION

Three insights are lacking from these input–output approaches to brain dynamics. The first insight is that the tissue formed by neurons in animal brains is unique. There is no other substance like neuropil in the known universe. Phylogenetically it has emerged by evolution repeatedly and independently in the brains of molluscs, crustaceans, and vertebrates, always as the basis for adaptive, goal-directed behavior. Being unlike anything else, it offers us the opportunity to discover its ''laws'', which might constitute the ''new laws of physics'' sought by Penrose (1989). Second, it follows that the machine metaphor cannot be serve to identify brain state variables with the state variables of any other machine. Third, brains organize their own goals, which machines cannot now do.

The second insight holds that, while neural activity is based in flows of transmitter molecules, inorganic ions, and electric currents fueled by metabolic energy and controlled by conformational structural changes in cell membranes, and while it carries both meaning and information, it cannot be defined by any of these physical or conceptual quantities. As noted by Karl Lashley the terms ''nerve force'', ''nerve energy'', ''information'', and ''representation'' are *metaphors* and not measurable descriptors of brain events. The spatiotemporal dynamic patterns of neuroactivity are observed by its electrochemical manifestations (''signs'' according to Adrian, 1947), but neuroactivity cannot be observed directly, and models of it must include transforms that describe postulated relations of the signs to the activity (Freeman, 1975). The contents of the signs are inferred from behavioral correlates and introspection (Freeman, 1991, 1995), which are used to characterize and model the operations by which brains construct *meanings* from sensory stimulation. *This is not ''information processing''*. The problem is, how to define neuroactivity? Just as ''force'' in physics is defined as a relation between mass, time and distance, ''neural activity'' must be defined by relations between its electrochemical signs and overt, measured behaviors. Neuroactivity does not flow across the receptors, the muscles, or the blood–brain barrier as energy, matter and information do. Brains are closed systems with respect to meaning, though not to energy or information. This enclosure explains the inaccessibility of qualia between brains, because the feelings and the associations in experiences that come in each brain with expectations, actions, and stimuli are rooted in its undivided body of past learning and its present chemical state.

The third insight is that the patterns of neural activity are endogenous. Their structure emerges from within and is not imposed solely by flows of energy, information or quanta from the bodies. The theory of chaos in nonlinear dynamical systems offers a set of techniques for describing the conditions required for emergence of self-organized patterns (Freeman, 1992, Skarda and Freeman, 1987). The process of self-determination is inherent in the Aquinian concept of intentionality (Martin, 1988, Pegis, 1948) by which each soul (mind/brain) intends (''stretches forth'') outside itself and into the world. It acquires knowledge by shaping itself (learning) in accordance with the effects (sensory feedback) of its endogenous action. The soul creates itself and its virtue by its own actions. Descartes discarded this medieval doctrine and mechanized the body by relegating perceptual events to the status of ''representations'' of the world, so the soul understood through logic, not prelogical learning. Kant deliberately revolutionized the mechanization by postulating that the rules of knowing were embedded as absolute ideas in human nature. He had no framework in Newtonian science to cope with the emergent processes of intentionality. Brentano and Husserl reintroduced the word as denoting what the Kantian representations were ''about'', whether or not the objects or events so represented actually existed in the world (Freeman, 1995). This meaning now constitutes the mainstream interpretation among analytic philosophers (Putnam, 1990).

6. NONLINEAR BRAIN DYNAMICS AND NEUROEXISTENTIALISM

The neo-Aristotelian philosophy of the later Middle Ages brooked no doubts about the unique causal efficacy of each person. The machine metaphor undermined that certainty and induced conflicts between ideas of free will and universal determinism that persist into the modern era. Several philosophers in the present century constructed powerful theories that avoided the machine metaphor and did not lead to the cruel dichotomy. The earliest were John Dewey with American pragmatism, Henri Bergson with ''Creative Evolution'', Martin Heidegger with ''Being and Time'', and Jean Piaget with developmental psychology. Sir Frederic Bartlett (1932) described the problem from the viewpoint of his studies on remembering:

> ...some widely held views [of memory] have to be completely discarded, and none more completely than that which treats recall as the re-excitement in some way of fixed and changeless ''traces'' (p. vi).
>
> The picture is one of human beings confronted by a world in which they can live and be masters only as they learn to match its infinite diversity by increasing delicacy of response, and as they discover ways of escape from the complete sway of immediate circumstances (p. 301).
>
> There is one way in which an organism could learn how to do this. It may be the only way... An organism has somehow to acquire the capacity to turn round upon its own ''schemata'' and to construct them afresh. This is a crucial step in organic development. It is where and why consciousness comes in; it is what gives consciousness its most prominent function... I wish I knew exactly how it was done (p. 206).

Jason Brown (1977) described it from a philosophical viewpoint:

> The structural organization of cognition is no less dynamic than the psychological systems it supports... The incessant flow of cognition, the continual appearance and disappearance of new form at each moment of our waking and sleeping life, are manifestations of the activity of the structure as a whole as it achieves one or another level of realization (pp. 2–11).
>
> Affect is not an energy that invades and charges an idea... There is no need for the concept of psychic energy (instinct, motivation) as a motivating force in cognition. The orderly sequence and unfolding of cognitive levels repeats and extends the phylogenetic and ontogenetic pattern. The progression from depth to surface, the incessant repetition of developmental form, and the striving toward higher levels are all part of an evolutionary trend that leads in a forward direction simply because it is in the nature of the organization to unfold in this manner (pp. 127–133).

Ilya Prigogine (1980) has applied his theory of ''dissipative structures'', which feed on energy and evolve complex patterns in states that are far from equilibrium, to understand the nonlinear dynamics of brains. Hermann Haken (1983) has applied his theory of synergetics to comprehend the physical principles, by which masses of neurons can interact to generate spatiotemporal patterns of activity.

Only one of several theories was effectively linked to neurobiology by its author. Maurice Merleau-Ponty (1942, 1945) drew heavily on work in clinical neurology from the First World War, particularly describing the phenomena now known as phantom limb and sensory neglect in brain-damaged individuals. With careful reasoning over voluminous biological details, he discarded the ''materialist'' view that minds were the results of linear causal chains of reflexes and chemical reactions. He likewise dismissed the ''idealist'' Kantian and Husserlian views of minds consisting of collections of representations, that were processed according to logical algorithms. He proposed instead the ''existentialist'' view, taken from his teacher, Heidegger, and classmate, Sartre: mind is ''the structure of behavior'', that creates itself by circular causality in its own ''action–perception cycle'' (Freeman, 1995).

7. THE NEUROBIOLOGY OF INTENTIONALITY

These several theories provide the warp and woof with which to weave the pattern of a strong neurobiological theory of self-organization of mind and brain. Biologists offer observations of the space–time patterns from brain imaging of human and animal brains during the performance of intentional behavior. Psychologists offer the measurements and analyses of behavior, in order to provide the essential behavioral structures that are to be correlated with the brain data. Physicists offer the dynamical systems theory by which to model the data and verify the capacity for brains to create and evolve their own unique space–time patterns of neural activity. Philosophers offer the conceptual framework required to bring the large picture into focus. The question remains: how do brains work? After three centuries of dynamics, answers are still elusive.

Nonlinear dynamics gives the technical tools needed to learn how it is done. The concept of the self-organizing brain, with its ever-shifting basins and attractors, its evolving trajectories (Tsuda, 1991), and its global cooperativity, enables us to model brain functions that transcend the present limitations of computational and representational schemata, and enter into those domains of nonrational and nonlogical construction from which consciousness emerges.

The complementary foundation in the mental sciences has been built in the past century by outstanding philosophers and psychologists, who can be grouped under the term ''existentialists'', and whose work has remained outside the main stream of modern neurobiology, owing to the unsolved problem of self-organization. The essential message of existentialism is that humans—and animals—create themselves by their actions. This insight has been arrived at independently in the 20th century by (among others):

Dewey (1914): Pragmatism—''Actions are not reactions to stimuli; they are actions into the stimuli.''
Heidegger (1927) and his students, Sartre and Merleau-Ponty (1942): Existentialism—''Mind is the structure of behavior.''
Koffka (1935): Gestalt psychology—''a field of force between objects and our Egos...leads to action.''
Piaget (1930): The cycle of ''action, assimilation, and adaptation'' in the sensorimotor stage of childhood development.
Gibson (1979): Ecopsychology—''An affordance...of an object offers what it does because it is what it is.''

In each of these systems sensation takes place as part of an ''action–perception cycle'' that Merleau-Ponty (1942) described as ''circular causality'' to contrast it with the ''linear causality'' of conditioned reflex chains and machine metaphors of brain function, such as clocks, telegraph nets, thermodynamic engines, chemical reaction systems, computers and holographs. Animals and humans receive and perceive stimuli as the end result of goal-oriented search for knowledge in the environment, and they learn about the world and shape themselves accordingly entirely in terms of the consequences of their own actions. The word ''intentionality'' has three widely accepted meanings. In analytic philosophy it means that a thought, belief, word, phrase or mental act is ''about'' something, whether an object or a person or a state of affairs, whether in the world or in the mind. In the psychological sciences it means that a thought, action or speech has a purpose, goal or intent, which is both outwardly directed toward manipulating objects in the world and inwardly directed toward satisfying biological drives, needs or instincts. In medicine it refers to the process of healing from injury, the re-establishment of wholeness of the body (Freeman, 1995). All the meanings stem from Medieval philosophy, which was synthesized in the 13th century by Aquinas. The mind is conceived as having unity that serves to distinguish itself from nonself; wholeness that expresses its direction of growth to maturity and the full realization of its potential; and intent (''stretching forth''), by which mind thrusts itself into the nonself by the actions of its body, and learns about the world by shaping itself in accordance with the outcomes of its actions, namely by learning from the sensory stimuli that were sought by its own actions (Freeman, 1995).

The neural mechanisms for intentionality in invertebrate animals and humans clearly reside in the limbic system. The evidence for this conclusion comes from diverse areas of study of animal and human behavior. Comparative neuroanatomists have shown that the forebrain of the most primitive surviving vertebrates representative of the ancestral line is composed of the essential sensory, motor and associational parts of the limbic system, including the primordial hippocampus, septum and amygdala (Herrick, 1948). Selective lesions brains have shown that removal of the entire neocortex but sparing the ancient limbic structures impairs sensory guidance and elaboration of behavior, but the impoverished actions are clearly identified as intentional (Broca, 1973, Goltz, 1874). Intentional actions must take place within a space–time matrix for spatial orientation (the ''cognitive map'') and temporal integration (''short-term memory''). Electrophysiological investigations of the hippocampus (O'Keefe and Nadel, 1978) combined with studies of selective lesions of the hippocampal formation (Milner, 1966) have shown the importance of the limbic system for this matrix. An essential role in intentional action is played by ''corollary discharge'' (Sperry, 1950) and reafference (Kay, 1994) first identified by von Helmholtz (1879), which clearly is focused in the entorhinal cortex through its dense reciprocal connections both with the hippocampus and with all primary sensory cortices (Lorente de Nó, 1934) and the frontal lobes (Freeman, 1995).

8. CONCLUSIONS

Electrophysiological studies of visual, auditory, somatic and olfactory EEGs (Barrie et al., 1996) have shown that spatial patterns of neural activity emerge by construction with each act of perception, and that they depend on the context of the present and equally on the past experience of each subject, not merely on the stimuli. This is a reflection of the unity of function of the forebrain.

The implication is that each perceptual act has been organized in the context of the present state of the limbic system, expressing a desired state that is elaborated into a plan of action and an expectancy of the sensory consequences of that action (Freeman, 1995). All past experience is available and operating in the global dynamical state of the forebrain with each act in a continual succession of acts. The objective aspect that is observable by behaviorists is the flexible and adaptive sequence of acts from which intent is inferred. The subjective aspect is consciousness within the individual of the context that is brought to bear in each moment of choice with each act.

By this interpretation there is little further to be said about the biology of consciousness, because animals cannot describe their states of awareness using language, and the requisite electrophysiological studies in humans are not admissible. Problems abound in the biology of intentionality, including the dynamics by which structure emerges from the chaos of neural activity, by which limbic activity patterns are re-shaped into commands into the motor systems and corollary discharges into the sensory systems, and how the chain of nuclei in the brain stem that provide the neurohormones bathing the entire forebrain are integrated into the intentional structure of brain activity. These may not constitute ''the hard problem'' of Chalmers (1996), but as several authors have commented (Hameroff et al., 1996), they are hard enough for this generation of researchers.

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