# Nonlinear Neurodynamics of Intentionality

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Study of electroencephalographic brain activity in behaving animals has guided development of a model for the self-organization of goal-directed behavior. Synthesis of a dynamical representation of brain function is based in the concept of intentionality as the organizing principle of animal and human behavior. The constructions of patterns of brain activity constitute meaning and not information or representations. The three accepted meanings of intention: "aboutness," goal-seeking, and wound healing, can be incorporated into the dynamics of meaningful behavior, centered in the limbic system interacting with the sensory and motor systems. Evidence is noted for the maintenance in cortical neuropil of a felt work of synaptic connections, that have incorporated past experience by changes in learning, and that act as a unified whole in shaping each intentional action at each moment. This constitutes the intentional structure of the brain. Meaning is a focus having a place without edges in this structure. The focus continually moves through it along a chaotic trajectory; the meaning occupies the whole structure. In this view, consciousness is the active state of an intentional structure, and awareness is the subjective aspect of the shifting focus.

The conviction is widespread though not universal among cognitive scientists, philosophers and physicists that "consciousness" has been wrongly excluded from modern science, and that systematic exploration should be undertaken to remedy the neglect (e.g., Crick, 1994; Dennett, 1991; Searle, 1992). The failure of many present-day psychologists and neurobiologists to join this endeavor with enthusiasm cannot be ascribed to ignorance, narrow-mindedness, or lack of the hubris required to tackle the "difficult problems." Neurobiologists with any sense of history are well aware of their many and fruitful contributions to research on consciousness, including the development of the fields of anesthesiology, psychoanalysis, mood and affect control,

psychedelics, and the neurotoxicology of altered states of mind, all of which have had roots in neurobiology.

Notably, biologists have enriched our knowledge about consciousness without transforming the concept. Some of the advances of the past half century are the following discoveries: (a) the induction of sleep by electrical stimulation of the thalamus of waking cats (Hess, 1954); (b) the electroencephalography of REM sleep and its relation to dreaming; (c) the role of the mesencephalic reticular formation in waking and generalized arousal (Magoun, 1958); (d) the role of the thalamic reticular formation in focused attention (Penfield and Jasper, 1954); (e) behavioral correlates of "40 Hz" rhythms (e.g., Sheer 1989); (f) the roles of the hypothalamus and of the neurohormones in emotions (Cannon, 1939; Masserman, 1943/1962); (g) the roles of the amygdaloid nucleus, hippocampus, and other parts of the limbic system in emotional expression (Bard, 1956; Klüver and Bucy, 1933/1962; Papez, 1929); (h) of "cognitive maps" (Tolman, 1951/1967) and of the roles of the hippocampus in memory with respect to temporal and spatial orientation (e.g., O'Keefe and Nadel, 1978); (i) the behavioral consequences in humans of section of the major cerebral commissures (Sperry, 1969); and (j) the localized changes in cerebral blood flow that have been described more recently by many to accompany differing kinds of mental activity. However, the terms of the debate have been slow to change despite these results. With important exceptions (e.g., Damasio, 1994) most researchers still try to find memories in the temporal lobe, emotions in the amygdala, cognitive maps in the hippocampus, linguistic operations in Broca's and Wernicke's areas, holistic thinking in the right hemisphere, consciousness in Penfield's (1975) centrencephalon, and so on.

To posit consciousness and the unconscious as the objects of scientific and philosophical inquiry is implicitly to invoke the classical antinomies of brain–mind or body–soul. For unabashed dualists such as Descartes (1641/ 1946) and Eccles (1994) the problem is to determine the sites of causal interaction between them, be they the pineal body or the molecular matrices of subsynaptic neural membranes. In their attempt to resolve the dichotomy, monists have proposed that consciousness and neural activity are complementary "aspects" of the same thing (Searle, 1992), which leads the problem far from biology. Whitehead (1938) conceived that particles do not exist as "dead matter" but as "events" that have objective, material aspects and subjective, experiential aspects. His "panexperientialism" has re-emerged in views expressed by Herbert (1993) and Penrose (1994), in accordance with which consciousness is provided through quantum coherence, and by which the problem is transferred to the field of quantum mechanics. The differences between the experiential aspects of quanta, atoms, stones, and humans

are treated as matters of complexity of organization. The details are left to the biologists, who are nonplused by this aspectual dualism.

Alternative formulations by pragmatists such as James (1890) and Dewey (1927) have conceived consciousness as existing only in the context of social relationships, so that it cannot be legitimately defined outside the field of social psychology, again leaving biologists without sufficient grounds on which to base their experimental research into its mechanisms. Likewise, Freud (1895/1954) abjured his early attempts to formulate a biological foundation for psychology, so that he and his followers spent the balance of their careers introspectively examining consciousness and its Platonic antithesis, the unconscious, individually with their patients, one-on-one. When transferred to fields of sociology, psychoanalysis, or law, the problem is made inaccessible to biotechnology.

## A Shift in Focus of Attention

Given that current efforts to deal with the problem of consciousness have led either to its dismissal (Dennett, 1991), trivialization (Crick, 1994), or transplantation to fields outside of biology, my view is that an alternate approach may be called for. Rather than pursuing forthrightly the elusive concept of consciousness, I suggest that an alternative target be formulated. For me that target lies in the area of goal-directed behaviors, overlapping largely but not completely with what are commonly called "voluntary" actions (Smith, 1994), whether or not they are conscious. These behaviors emerge from within brains, in contrast to evoked or reflex actions, and their flexibility and adaptiveness in the face of unexpected obstacles belies the possibility of genetic or environmental programming. The experimental, mechanistic question is: How can populations of neurons in brains generate the neuroactivity patterns directing these movements? A useful set of theoretical tools with which to seek answers is to be found in the self-organizing properties of nonlinear dynamic systems. The theoretical, philosophical question is: What principle or organizing concept can be adopted to supplant the notion of consciousness? My choice of focus is the term "intentionality."

There are three widely accepted meanings for this term. In analytic philosophy it means that thought, belief, word, phrase or mental act is "about" something, whether an object or a person or a state of affairs, and either in the world or in the mind. In behavioral 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 thirteenth century by Aquinas. Aquinas conceived the mind as having unity that served to distinguish itself from nonself; wholeness that expressed its direction of growth to maturity and the full realization of mind's potential; and intent ("stretching forth"). Through intent 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).

Intentionality was buried by Descartes and most deliberately by Kant, in a revolution in which the inner structure of pure reason was posited as fundamental to human nature, and the access by humans to the realities of the world was limited and obscured by the imperfections of the experimental sciences (Kant, 1781/1929). The concept was resurrected by Brentano, a close reader of Aquinas, and elaborated by Husserl in the early part of this century, but in crucially different form. In accord with Kant, intentional states were re-defined as mental representations of objects, that were manipulated according to logical rules, constituting the categories of reason. The problem of representationalism has been, and still is, how to treat the unbounded and unmanageable "aboutness" of the representations (Putnam, 1990). Other forms taken by the impasse are the "binding problem" of connecting features to represent an object (Hardcastle, 1994; Tovée and Rolls, 1992); the difficulty of attaching meaning to symbols (Dreyfus, 1979) or, comparably, of attaching soul to synaptic vesicles; and the indeterminacy of whether consciousness can exist in machines (Herbert, 1993).

The underlying concept, though not the term, has flourished in two other areas of the mental sciences, the American tradition of pragmatism through James and Dewey, and the European tradition of existentialism, in both of which the self creates and defines itself by its own actions into the world. The existential approach has been taken by psychologist Merleau–Ponty (1945/1962) in his phenomenology of perception, by Köhler, and Koffka in pursuit of the interactive field of the Gestalt, by J.J. Gibson in the form of "affordances," and by Shaw, Kugler and Kinsella–Shaw (1990) in the field of ecological psychology. Their problem has been, and still is, how to devise biologically sound models of those activities of nerve cells that can culminate in the appearance of intentional behavior. To paraphrase Searle (1995), how can the meaningless firing of neurons give rise to meaningful activity of the body in its reaching for a desired object?

My purpose here is to describe a view in which nonlinear neurodynamics can unify these three meanings of intentionality, explaining "aboutness," the genesis of goal-oriented actions, and the actualization of genetic potential in

terms of the interactions of large populations of neurons. The way to do this is to ask whether brains make representations of objects and goals? Of course, brains do this outside themselves for the purpose of communication between brains in speech, symbols and gestures, but does a brain make representations within itself for communication between its own parts, its sensors, and its effectors? Do trains of action potentials represent persons and objects, as words in a book do? This interpretation is so easy, obvious and commonsensical, that it has become the bedrock of modern neurobiology, and it seems quixotic or even querulous to question it. Yet this idea presents a solid target for demolition, because it is an obstacle blocking further progress.

### An Experimental Test Between Representationalism and Existentialism

A crucial test of representationalism is to find a representation of an object in a brain. This should be a spatial pattern of neural activity, which is invariant under repeated presentation of the same stimulus to an array of sensory receptors. The olfactory system is a good test bed, because there is a minimum of preprocessing between excitation of the receptors and the genesis of a cerebral response in the olfactory bulb. The receptor neurons have over a thousand types of selective chemical sensitivities, and there is some evidence that the axons of each type are converged by growth factors to local synaptic nests in the bulb called glomeruli. The receptor neurons in the nose that are sensitive to any one odor are widely scattered, and each sniff excites a different subset, so some neural mechanism for generalization is required to classify inputs. This is provided by Hebbian (1949) learning, because on repeated exposure to an odorant made significant by pairing it with a reinforcing unconditional stimulus, a nerve cell assembly forms by the strengthening of synapses between co-activated bulbar neurons, so that after learning, the excitation of any members of the training set of receptors cause the stereotypic excitation of a bulbar cell assembly. The receptor activity in the nose and the evoked activity in the bulb are both spatial patterns of selectively activated neurons, which persist for the duration of a sniff.

Experiments were conducted in cats and rabbits by placing arrays of 64 electrodes on the olfactory bulb, allowing for recovery from surgery, and then presenting a series of odorants to untrained animals while seeking related spatial patterns of bulbar electroencephalographic (EEG) activity. Only one pattern of amplitude was found, which was unique and constant for each animal (Freeman, 1978). It had the form of a spatial pattern of amplitude modulation of an oscillatory burst of EEG at the same frequency in all 64 traces over the array. The animals were then conditioned to respond to selected odors, and with each learned odorant a new spatial pattern appeared, but it was also pre-

sent between odorant presentations (Freeman and Schneider, 1982), leading to the conclusion that the spatial pattern prior to the arrival of the stimulus was a representation of an expected odorant, namely a search image (Freeman, 1983).

This raised the question, how could the bulb signal the presence versus the absence of an expected odorant, if the search image and the representation had the same spatial pattern of EEG amplitude? The hypothesis was put forth that the oscillations of the bulbar neurons at the common frequency would be dispersed in phase during anticipation, so that in summation of the activity by the targets of bulbar transmission, the bulbar output would be weak, but with arrival of the expected stimulus, the phase distribution should collapse leading to strengthening of the bulbar output (Freeman, 1979). This proved to be a variant of the "binding hypothesis" of Milner (1974) and von der Malsburg (1983).

Initially the measurements of phase on the 64 EEG traces appeared to confirm the hypothesis (Bressler, 1988; Freeman, 1980). Subsequent experiments with improved measurement techniques falsified it. There was no collapse of the phase vector (Freeman and Baird, 1987). Moreover, in contrast with early results having inadequate precision of measurement, differences in EEG amplitude pattern were detected and then verified between the pre-stimulus and the stimulus time periods, coming from respectively the control state and an odorant receiving state (Freeman and Viana Di Prisco, 1986). Further, no spatial pattern could be localized to limited parts of the bulb that might correspond to a putative nerve cell assembly. Every neuron in the bulb participated in every response to a learned odorant. The spatial patterns of bulbar phase and amplitude could in no way be derived from spatial patterns of receptor activity by preprocessing. They could only occur as the result of a dynamic state transition of the entire olfactory bulb with each inhalation (Freeman, 1990). Most importantly, the spatial patterns of amplitude were not invariant with respect to stimuli. Any change in the experiment such as by introducing a new discriminant odorant, forcing generalization across the odorants, or switching the reinforcement contingency in discriminative conditioning between the rewarded and unrewarded conditioned stimuli, was accompanied by small changes in all pre-existing amplitude patterns, including that for the control period (Freeman, 1991). Hence the hypothesis that bulbar activity evoked by an odorant represented that odorant was abandoned (Skarda and Freeman, 1987).

## A Hypothesis on the Neurodynamics of Intentionality

In its place a new hypothesis was devised, according to which the olfactory bulb is a nonlinear dynamic system, which is destabilized by sensory input, leading to the endogenous construction of its own spatiotemporal patterns of activity (Freeman, 1987). It is a self-organizing system having multiple chaotic

attractors with their attendant basins of attraction, and the capability for rapid global state changes from each attractor to the next, under controls from the receptors, the neuromodulatory nuclei in the brain stem, and other areas of cortex. Evidence has been accumulated that the visual, auditory, somatic and entorhinal neocortices operate in accordance with the same or similar dynamics (Barrie, Freeman, and Lenhart, 1996; Freeman and Barrie, 1994; Kay, 1994). Since all sensory systems interact with the entorhinal cortex and thereby indirectly with the hippocampus, since they share the same basic dynamics, the cortical components of the limbic system must likewise maintain self-organizing dynamics and attractors giving spatial patterns of amplitude modulation of chaotic carrier waves.

Here is a key to unlock the problem of intentionality. The great masses of interactive neurons comprising the limbic system, however it is defined (and there is a continuing disagreement as to its definition among those who work with it), are clearly capable of constructing complex patterns of activity, as evidenced by sustained background activity that changes with the modifications in behavioral state from sleep to waking, from rest to activity, and so on. Reviews of the phylogenetic history of vertebrate brains, and of the effects of surgical lesions in the forebrain on exploratory behavior, clearly indicate that the neural mechanisms for intentional behavior reside in the limbic system and support the convergence of all sensory inputs into the entorhinal cortex, the integration over time and in spatial coordinates within the hippocampus, and the return of the integrand back to the entorhinal cortex for re-distribution to all sensory systems. Every goal-directed action is in the world and must be supported within a space–time neural framework, that is, in contemporary jargon a cognitive map and a short term memory, that are required for orientation of actions in time and space.

The modification of the self that was envisioned by Aquinas is compatible with the learning that is known to be mediated by the hippocampal formation in the ongoing construction of an intentional life history. The hippocampus is not the locus of storage. On the contrary, the synaptic modifications are distributed in all parts of the forebrain. The evolutionary changes in the spatial patterns we have observed in the EEGs of the olfactory, visual, auditory and somatosensory cortices reflect the participation of all of these structures, each emphasizing those aspects which are pertinent to its own specialized receptor inputs. Recent experiments have demonstrated the existence of the reafferent messages from the entorhinal cortex to the olfactory bulb (Kay and Freeman, 1994), and the rapid and repetitive exchanges that occur between these structures and the prepyriform cortex in the performance of elementary appetite conditioned reflexes.

Intentional acts can be described as based in the on-going dynamic construction in the limbic system of directed motor patterns, that are delivered

through the amygdala and septum into the lateral and medial forebrain bun-
dles to the subthalamus and hypothalamus, thence into the musculoskeletal,
autonomic, and neuroendocrine effector systems. With each descending
motor pattern there is concomitant transmission of corollary discharges to all
sensory systems, in order to prime them for attending to expected input and
update then in respect to the expected consequences on their input, which
occur owing to the motor displacement of the receptors, and which are about
to change the sensory stream (Freeman, 1995). The unity of the perceptual
experience, including the entire history and present context unique to each
subject, can be accounted for by the convergence of perceptual flow into the
limbic system, prior to its transfer into the hippocampus. At each moment
the structure of intentional action extends throughout the forebrain, based
in the seamless fabric of cortical neuropil (the tissue comprised of immense
numbers of neurons interconnected by axons and dendrites); its embodiment
of all past experience lies in its synaptic modifications through learning.
Such modifications are widespread through the forebrain with each act of
learning, owing to the patterns of diffuse projections of the aminergic sys-
tems that implement the synaptic changes that effect associative learning.

A solution to the problem of "aboutness" is offered by the properties of
neuropil, and by the characteristics of the evolution of EEG patterns in each
subject under the impact of cumulative experience. Each perceptual event
lasting on the order of a tenth of a second in sensory cortex can be seen as
shaped in part by the microscopic sensory input, but in large part by the
weights of the multitudinous synapses in the neuropil, the transient impact
of signals from the entorhinal and other associated cortices, and the base
notes provided by the neuromodulator inputs from aminergic and peptidergic
nuclei in the hypothalamus and brain stem. Each state transition is guided
into a new basin of attraction by all these influences in concert, and the
resulting spatial pattern of activity in varying degrees manifests all of them.
This multideterminacy within the self comprising the active brain supports
the conclusion that each perceptual construct reflects the entire corpus of
past experience. An appropriate term for the outcome is that the percept
constitutes not a representation of a stimulus. It is the meaning of the stimu-
lus for the self. Meaning conceptually is a set of relationships, more generally
a place in a structure. The structure is intentional experience, and the focus
is that which has been selected by the combination of motor action (inten-
tion), selective preparation by reafference (attention); and the actualization
of the state transition by the arrival of a sensory-evoked volley of action
potentials injected into the sensory cortex (sensation). The particular nerve
cell assembly activated serves to guide the cortex into the appropriate basin
of attraction already prepared, culminating in the perception by integration
and construction in the limbic system.

## A Pathway for Testing the Hypothesis

Dynamics is the study of change through space and time. In order to apply it we must define that which changes, the state variable, represent it by a symbol, express it as a state at a given time numerically, and then describe how it changes as a function of time and space. We must choose the scales in terms of microseconds or minutes and microns or meters, and we must conceive of a hierarchy of subsystems and suprasystems around the domain of choice. Typically for brain studies we choose neurons measured in microns and their action potentials measured in microseconds. We must give inputs such as sensory stimuli and measure outputs such as muscle contractions. By constructing a matrix of differential equations, in which the output is set equal to the input, we define the operation by which the one is transformed into the other. In this manner biologists commonly construct what Merleau–Ponty (1945/1962) called a "linear-causal chain," by which a stimulus is transformed into action potentials, these are integrated by central neurons, the central excitatory state is transformed into motor action potentials, and these into muscle contractions. We have superb systems of equations to describe these operations at the levels of the brain and spinal cord (Basar, 1980; Freeman, 1975; Houk, 1974; Nunez, 1995).

Where linear causality breaks down is in the response of sensory cortex to the thalamocortical volley that mediates the terminal stage of sensory transmission. The macroscopic mass of cortical neurons forming densely interconnected neuropil is destabilized by the microscopic input, and by virtue of a nonlinear state transition, it jumps from one wing to another of a global attractor developed and maintained by the cortex through learning (Freeman, 1992). The spatial pattern of activity that is shaped by the attractor is measured in scales of millimeters and fractions of a second. It "enslaves" (Haken, 1983) the neurons comprising the mass and thereby determines the global output of the cortex. It is the action potentials of the individual neurons at the microscopic level that carry the output, but it is the macroscopic pattern that is extracted by the targets of cortical transmission by virtue of spatial integration (Freeman, 1991). The global pattern is shaped in small part by the microscopic input but in larger part by the preexisting synaptic network that is shaped by past experience and by the excitability of the neurons that is shaped by the interplay of diverse neurohormones and neuromodulators. It is possible to describe statistical relationships among these diverse factors, but it is not possible to assign unequivocal causal relationships, in the manner that is feasible for simple feedforward circuits. Given the contextual dependency of cortical responses, including the behavioral history and current brain state, we say that the cortical output constitutes the significance, value, and meaning of

the stimulus. It is not a representation of a stimulus, nor is it derivable from the stimulus by any sequence of filter operations such as serve to define "feature detector" neurons.

The necessary dynamic equations have been elaborated for the olfactory system (Chang and Freeman, 1996; Freeman, 1987; Kay, Shimoide, and Freeman, 1995; Shimoide and Freeman, 1995; Yao and Freeman, 1990), but have not yet been developed for the sensory neocortices or for the major components of the limbic system. Even such elementary measurements as the time and space constants of neuron populations in the open loop state under deep anesthesia have yet to be made. If the rate of progress to date is a valid indication, several decades may elapse before a solid experimental foundation for understanding the neurodynamics of the limbic system is constructed.

## Conclusion

Neurodynamics can support testable hypotheses on intentionality and explain its properties of unity, ("aboutness"), wholeness, and goal-directedness. It is built on the assumption that minds and brains co-evolved in the phylogenetic history of animals, with increasing complexity but otherwise constancy in the basic principles of neural self-organization. Intentional behavior is instantly and unequivocally recognizable in diverse animals, including people, bats and even bees and octopuses. However, dynamics in itself does little to clarify the natures of consciousness and awareness, which remain conjectural even in species most like ourselves. At some elementary level, consciousness can be regarded as the existence of an active focus, and the unconscious as everything else in the intentional structure. There are no edges or compartments in meaning. Moreover, the most important aspect of consciousness is the relationship that it posits between brains. In accordance with the view of John Dewey (1927) the declaration that a subject is conscious conveys an expectation of an exchange between two or more intentional subjects. It is a social contract and an expectancy of understanding (Freeman, 1995) of readiness to act toward another individual that is about to take place. Direct applications in the form of psychodynamics and sociodynamics remain metaphorical. An attempt to reify consciousness as a state, process, or causal operator within an individual brain misses the context in which the term derives its operational meaning, such as is used when someone knocked out regains consciousness and resumes normal interactions with family and friends.

With respect to the self, each goal-directed action is in-formed by the intentional structure, so that experience is always available in the waking state, without need for look-up tables and template matchings. This interpretation suggests that consciousness is the active state of readiness and availability of

the past, and that awareness is the chaotically shifting focus of meaning, most often snared by sensory-activated attractors, but sometimes migrating into the deep reaches of the intentional state space, far even from the human locus of the self. Both consciousness and awareness are intensely private. Unlike energy, matter and information, for which brains are open systems, meaning exists in a closed system. The only experience we can have is our own.

The success or failure of this hypothesis hinges on the disposition of representations. There are three main classes of theory of mind. The materialist/empiricist view is that mind is nothing but the firing of neurons and fluxes of neurotransmitters that implement chains of reflexes. Representation takes the form of information from sensory receptors, which is "processed" according to mechanistic rules. The cognitivist/idealist view holds that mind is a collection of representations, which are formed from sense data, stored, retrieved, and compared with new inputs formed by the binding of feature detectors as the basis of perception. Situated cognitivists (Slezak, 1994) distinguish between internal and external representations, there being correspondence between objects in the world and action patterns in brains. The intentionalist/existentialist view is that the mind is "the structure of behavior" (Merleau–Ponty, 1942/1963) and is continually creating itself by its directed actions and their sensory consequences through learning. Representations are material objects such as gestures, sound, odorants, and light waves that are shaped by motor actions for the purpose of communication between brains. There are no representations in brains, only meanings. Conversely, representations have no meaning, though they are shaped in accordance with meaning in transmitting brains and can instigate the construction of meaning in receiving brains. That dictum applies to the words on this page. They have no meaning. The author concludes with an expression of hope that they will spark the construction of meanings in the minds of readers, but acknowledges that those new meanings will not be the same as what was meant during the concatenation of the words.

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