The Neurodynamics of Intentionality in Animal Brains Provides the Basis of Intelligent Behavior

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Abstract

Intelligent behavior is characterized by flexible and creative pursuit of endogenously defined goals. It has emerged in humans through the stages of evolution that are manifested in the brains and behaviors of the vertebrate series. Intentionality is a key concept by which to link brain dynamics to goal-directed behavior. The archetypal form of intentional behavior is an act of observation into time and space, by which information is sought for the guidance of future action.

Key Words:

Brain dynamics, Chaotic construction, EEG, Intentionality, Perception

1. The neurodynamics of intentionality as it occurs in the behavioral action of observation

The first step in pursuit of an understanding of intentionality is to ask, what happens in brains during an act of observation? This is not a passive receipt of information from the world. It is a purposive action by which an observer directs the sense organs toward a selected aspect of the world and interprets the resulting barrage of sensory stimuli. The concept of intentionality has been used to describe this process in different contexts, since its first use by Aquinas 700 years ago. The three salient characteristics of intentionality as it is treated here are (a) intent or directedness toward some future state or goal, (b) wholeness, and (c) unity (Freeman 1995). These three aspects correspond to use of the term in psychology with the meaning of purpose, in medicine with the meaning of mode of healing and integration of the body, and in analytic philosophy

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mode of healing and integration of the body, and in analytic philosophy with the meaning of the way in which beliefs and thoughts are connected with ("about") objects and events in the world.

Intent comprises the endogenous initiation, construction, and direction of behavior into the world. It emerges from brains. Humans and animals select their own goals, plan their own tactics, and choose when to begin, modify, and stop sequences of action, and humans at least are subjectively aware of themselves acting. Unity appears in the combining of input from all sensory modalities into *Gestalten*, in the coordination of all parts of the body, both musculoskeletal and autonomic, into adaptive, flexible, yet focused movements. Subjectively, unity appears in the awareness of self. Wholeness is revealed by the orderly changes in the self and its behavior that constitute the development and maturation of the self, within the constraints of its genes and its material, social and cultural environments. Subjectively, wholeness is revealed in the remembrance of self through a lifetime of change.

1.1 The limbic system is the organ of intentional behavior

Brain scientists have known for over a century that the necessary and sufficient part of the vertebrate brain to sustain minimal intentional behavior is the ventral forebrain, including those components that comprise the external shell of the phylogenetically oldest part of the forebrain, the paleocortex, and the deeper lying nuclei with which the cortex is connected. These components suffice to support remarkably adept patterns of intentional behavior, in dogs after all the newer parts of the forebrain have been surgically removed (Goltz 1892), and in rats with neocortex chemically inactivated by spreading depression (Bures et al. 1974). Intentional behavior is severely altered or absent after major damage to the basal forebrain, as manifested most clearly in Alzheimer's disease.

Phylogenetic evidence comes from observing intentional behavior in salamanders, which have the simplest of the existing vertebrate forebrains (Herrick 1948; Roth 1987). The three parts are sensory (which, as in small mammals, is predominantly olfactory), motor, and associational. The latter part contains the primordial hippocampus with its associated septoamygdaloid and striatal nuclei, which are identified in higher vertebrates as the locus of the functions of spatial orientation (the "cognitive map") and temporal integration in learning (the organization of long and short term memory). These processes are essential, inasmuch as intentional action takes place into the world, and even the simplest action, such as searching for food or evading predators, requires an animal to know where it is with respect to its world, where its prey or refuge is, and what its spatial and temporal progress is during sequences of attack or escape .

1.2 Neurodynamic manifestations of intentionality in brain activity of the primary sensory cortices: the EEG

The crucial question for neuroscientists is, how are the patterns of neural activity that sustain intentional behavior created in brains? The answer is provided by studies of electrical activity of the primary sensory cortices of animals that trained to respond to conditioned stimuli (Freeman 1975, 1992, 1995; Barrie et al. 1996; Kay et al. 1996). Cortical neurons are selectively activated by sensory receptors to generate microscopic activity. By interactions among the cortical neurons a population forms that "binds" their activity into a macroscopic pattern (Haken 1983; Gray 1994; Hardcastle 1994; Singer and Gray 1995). The brain activity patterns that are seen in electroencephalograms (EEGs) reveal the macroscopic brain states that are triggered or induced by the arrival of stimuli.
These brain states are not representations of stimuli, nor are they the simple effects caused by stimuli. Each learned stimulus serves to elicit the construction of a pattern that is shaped by the synaptic modifications among cortical neurons from prior learning, and also by the brain stem nuclei that bathe the forebrain in neuromodulatory chemicals. It is a dynamic action pattern that creates and carries the meanings of stimuli for the animal. It reflects the individual history, present context, and expectancy, corresponding to the unity and the wholeness of the intentionality. The patterns created in each cortex are unique to each animal. All sensory cortices transmit their signals into the limbic system, where they are integrated with each other over time, and the resultant integrated meaning is transmitted back to the cortices in the processes of selective attending, expectancy, and the prediction of future inputs.

The same kinds of EEG activity as those found in the sensory and motor cortices are found in various parts of the limbic system. This discovery indicates that the limbic system also has the capacity to create its own spatiotemporal patterns of neural activity. They are related to past experience and convergent multisensory input, but they are self-organized. The limbic system provides a neural matrix of interconnections, that serves to generate continually the neural activity that forms goals and directs behavior toward them. EEG evidence shows that the process occurs in discontinuous steps, like frames in a motion picture. Each step follows a dynamic state transition, in which a complex assembly of neuron populations jumps suddenly from one spatiotemporal pattern to the next, as the behavior evolves. Being intrinsically unstable, the limbic system continually transits across states that emerge, spread into other parts of the brain, and then dissolve to give rise to new ones. Its output controls the brain stem nuclei that serve to regulate its excitability levels, implying that it regulates its own neurohumoral context, enabling it to respond with equal facility to changes that call for arousal and adaptation or rest and recreation, both in the body and the environment. It is the neurodynamics of the limbic system, assisted by other parts of the forebrain such as the frontal lobes, that initiates the novel and creative behavior seen in search by trial and error.

The limbic activity patterns of directed arousal and search are sent into the motor systems of the brain stem and spinal cord. Simultaneously, patterns are transmitted to the primary sensory cortices, preparing them for the consequences of motor actions. This process has been called "reafference" (von Holst and Mittelstaedt 1950; Freeman 1995), "corollary discharge" (Sperry 1950), "focused arousal" (Sheer 1989), and "preafference" (Kay et al. 1996). It sensitizes sensory systems to anticipated stimuli prior to their expected times of arrival Sensory cortical constructs consist of brief staccato messages to the limbic system, which convey what is sought and the result of the search. After multisensory convergence, the spatiotemporal activity pattern in the limbic system is up-dated through temporal integration in the hippocampus. Between sensory messages there are return up-dates from the limbic system to the sensory cortices, whereby each cortex receives input that has been integrated with the output of the others, reflecting the unity of intentionality. Everything that a human or an animal knows comes from this iterative circular process of action, reafference, perception, and up-date. It is done by successive frames that involve repeated state transitions and self-organized constructs in the sensory and limbic cortices. This neurodynamic system is defined here as the "limbic self" in the brain of an individual, where intentional behavior is created, with help from other parts of the forebrain.

An act of observation comprises Aquinas' intentional action of "stretching forth" and learning from the consequences, and the existential "action-perception cycle" of Merleau-Ponty (1942). It corresponds to Piaget's (1930) cycle of "action, assimilation, and adaptation" in the sensorimotor stage of childhood development. His postulated sequences of equilibrium, disequilibrium, and re-equilibration conform to state transitions in brain dynamics, which initiate and sustain action, construct dynamic patterns in the sensory cortices, and up-date the limbic patterns by modifying synapses in the learning that follows the sensory consequences of intended actions. For Piaget, cause and effect are chains of events that have the appearance of linkage corresponding to the unfolding experience of that exploration, by which a child is trying to make sense of its world by manipulating objects in it. The origin of causal inference is buried deeply in the pre-linguistic exploratory experience of each of us. It is not easily accessed by cognitive analysis or introspection.

We are all aware of our acts of observation. It is partly by expectation of what we are looking for through reafference, partly by perceiving the changes that our actions make in the dispositions of our bodies through proprioception, and partly by our selection of stimuli from the environment through exteroception. We perceive our intentional acts as the "causes" of changes in our perceptions, and the subsequent changes in our bodies as "effects" (Freeman 1995). If this hypothesis of limbic dynamics is correct, then everything that we know we have learned through the action-perception cycle, and the iterative state changes by which it is produced in brains.

2.0 Characteristics of brain states

The "state" of the brain is a description of what it is doing in some specified time period. A state transition occurs when the brain changes and does something else. For example, locomotion is a state, within which walking is a rhythmic pattern of activity that involves large parts of the brain, spinal cord, muscles and bones. The entire neuromuscular system changes almost instantly with the transition to a pattern of jogging or running. Similarly, a sleeping state can be taken as a whole, or divided into a sequence of slow wave and REM stages. Transit to a waking state can occur in a fraction of a second, whereby the entire brain and body shift gears, so to speak. The state of a neuron can be described as active and firing or as silent, with sudden changes in the firing manifesting state transitions. Populations of neurons also have a range of states, such as slow wave, fast activity, seizure, or silence. The science of dynamics is designed to study states and their transitions.

2.1 The problem of stability of cortical states

The most critical question to ask about a state is its degree of stability or resistance to change. Evaluation is done by perturbing an object or a system (Freeman 1975). For example, an object like an egg on a flat surface is unstable, but a coffee mug is stable. A person standing on a moving bus and holding on to a railing is stable, but someone walking in the aisle is not. If a person regains his chosen posture after each perturbation, no matter in which direction the displacement occurred, that state is regarded as stable, and it is said to be governed by an attractor. This is a metaphor to say that the system goes ("is attracted") to the state through an interim state of transiency. The range of displacement from which recovery can occur defines the basin of attraction, in analogy to a ball rolling to the bottom of a bowl. If the perturbation is so strong that it causes concussion or a broken leg, and the person cannot stand up again, then the system has been placed outside the basin of attraction, and a new state supervenes with its own attractor and basin.

Stability is always relative to the time duration of observation and the criteria for what is chosen to be observed. In the perspective of a lifetime, brains appear to be highly stable, in their numbers of neurons, their architectures and major patterns of connection, and in the patterns of behavior they produce, including the character and identity of the individual that can be recognized and followed for many years. Brains undergo repeated transitions from waking to sleeping and back again, coming up refreshed with a good night or irritable with insomnia, but still, giving the same persons as the night before. Personal identity is usually quite stable. But in the perspective of the short term, brains are highly unstable. Thoughts go fleeting through awareness, and the face and body twitch with the passing of emotions. Glimpses of their internal states of neural activity reveal patterns that are more like hurricanes than the orderly march of symbols in a computer. Brain states and the states of populations of neurons that interact to give brain function, are highly irregular in spatial form and time course. They emerge, persist for a small fraction of a second, then disappear and are replaced by other states.

2.2 Three types of stable cortical states

In using dynamics we approach the problem by defining three kinds of stable state, each with its type of attractor. The simplest is the point attractor. The system is at rest unless perturbed, and it returns to rest when allowed to do so. As it relaxes to rest, it has the history of what happened, but that history is lost after convergence to rest. Examples of point attractors are silent neurons or neural populations that have been isolated from the brain, and also the brain that is depressed into inactivity by injury or a strong anesthetic, to the point where the EEG has gone flat. A special case of a point attractor is noise. This state is observed in populations of neurons in the brain of a subject at rest, with no evidence of overt behavior. The neurons fire continually but not in concert with each other. Their pulses occur in long trains at irregular times. Knowledge about the prior pulse trains from each neuron and those of its neighbors up to the present fails to support the prediction of when the next pulse will occur. The state of noise has continual activity with no history of how it started, and it gives only the expectation that its amplitude and other statistical properties will persist unchanged.

A system that gives periodic behavior is said to have a limit cycle attractor. The classic example is the clock. When it is viewed in terms of its ceaseless motion, it is regarded as unstable until it winds down, runs out of power, and goes to a point attractor. If it resumes its regular beat after it is re-set or otherwise perturbed, it is stable as long as its power lasts. Its history is limited to one cycle, after which there is no retention of its transient approach in its basin to its attractor. Neurons and populations rarely fire periodically, and when they appear to do so, close inspection shows that the activities are in fact irregular and unpredictable in detail, and when periodic activity does occur, it is either intentional, as in rhythmic drumming, clapping and dancing, or it is pathological, as in the periodic oscillations of the eyes in nystagmus, or of the limbs during Parkinsonian tremor.

The third type of attractor gives aperiodic oscillation of the kind that is observed in recordings of EEGs. There is no one or small number of frequencies at which the system oscillates. The system behavior is therefore unpredictable, because performance can only be projected far into the future for periodic behavior. This type was first called "strange"; it is now widely known as "chaotic". The existence of this type of oscillation was known to Poincaré a century ago, but systematic study was possible only recently after the full development of digital computers. The best known simple systems with chaotic attractors have a small number of components and a few degrees of freedom, as for example, the double-hinged pendulum, and the dripping faucet. Large and complex systems such as neurons and neural populations are thought to be capable of chaotic behavior, but proof is not yet possible at the present level of developments in mathematics.

The discovery of chaos has profound implications for the study of brain function (Skarda and Freeman 1987). A chaotic system has the capacity to create novel and unexpected patterns of activity. It can jump instantly from one mode of behavior to another, which manifests the facts that it has a collection of attractors, each with its basin, and that it can move from one to another in an itinerant trajectory (Tsuda 1996). It retains in its pathway across its basins its history, which fades into its past, just as its predictability into its future decreases. Transitions between chaotic states constitute the dynamics we need to understand how brains do what they do.

3.0 The cortical state transition is the elemental step of intentionality

Systems such as neurons and brains that have multiple chaotic attractors also have point and limit attractors. A system that is in the basin of one of its chaotic attractors is legendary for the sensitivity to what are called the "initial conditions". This refers to the way in which a simple system is placed into the basin of one of its attractors. If the basin is that of a point or a limit cycle attractor, the system proceeds predictably to the same end state. If the basin leads to a chaotic attractor, the system goes into ceaseless fluctuation, as long as its energy lasts. If the starting point is identical on repeated trials, which can only be assured by simulation of the dynamics on a digital computer, the same aperiodic behavior appears. This is why chaos is sometimes called "deterministic". If the starting point is changed by an arbitrarily small amount, although the system is still in the same basin, the trajectory is not identical. If the difference in starting conditions is too small to be originally detected, it can be inferred from the unfolding behavior of the system, as the difference in trajectories becomes apparent. This observation shows that a chaotic system has the capacity to create information in the course of continually constructing its own trajectory into the future.

In each sensory cortex there are multiple basins corresponding to previously learned classes of stimuli, as well as to the unstimulated state. This chaotic prestimulus state of expectancy establishes the sensitivity of the cortex, so that the very small number of sensory action potentials evoked by an expected stimulus can carry the cortical trajectory into the basin of an appropriate attractor. The stimulus is selected by the limbic brain through orientation of the sensory receptors by sniffing, looking, and listening. The basins of attraction are shaped by limbic input to sensitize the reception of a desired class of stimuli. The web of synaptic connections that was modified by prior learning contributes to the formation of basins and to the attractors. This is an act of observation.

When the input conforms to some previous experience, such that it places the sensory cortex into the basin of a learned wing of an attractor, then the confinement of the cortical dynamical system to that wing gives rise to the spatial pattern of activity, that constitutes the active state leading to the behavior that is appropriate for the designated class of input, on the basis of prior experience. If, however, the input is novel, meaning that the animal (or human) has no prior experience with it, and that it does not correspond to a learned class of input, then the cortex fails to access any wing of its global attractor. The result is the failure of an oscillatory burst to occur, with no action pattern that can assign the associational and/or motor systems to which the sensory cortex transmits to an attractor for the organization of a stimulus-specific behavior. That failure constitutes a departure from the background state, meaning that the burst that is expected with each perceptual act such as a sniff or a glance does not take place as expected. That failure is in itself a signal, which results in the induction of an orienting response: directing of the head, eyes, ears and nose in search of something unknown that may be important. There is also the expectancy of a reinforcement of some kind, either pleasant or painful. If reinforcement does occur, then learning takes place, leading to the formation of a new wing of the global attractor. If it does not occur, then habituation takes place, and the novel stimulus is incorporated into the background. Both of these forms of learning support the intentional process of observation in the future exposure to the previously novel input.

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