The neurobiological infrastructure of natural computing: Intentionality

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Abstract

Brains and computers are both dynamical systems that manipulate symbols, but they differ fundamentally in their architectures and operations. Human brains do mathematics; computers do not. Computers manipulate symbols that humans put into them without grounding them in what they represent. Human brains intentionally direct the body to make symbols, and they use the symbols to represent internal states. The symbols are outside the brain. Inside brains the construction is effected by spatiotemporal patterns of neural activity that are operators, not symbols. The operations include formation of sequences of neural activity patterns that we observe by their electrical signs. The process is by neurodynamics, not by logical rule-driven symbol manipulation. The aim of simulating human natural computing should be to simulate the operators. In its simplest form natural computing serves for communication of meaning. Neural operators implement non-symbolic communication of internal states by all mammals, including humans, through intentional actions. The neural operators that implement symbol formation must differ, but how is unknown, so we cannot yet simulate human natural computing. Here I propose that symbol-making operators evolved from neural mechanisms of intentional action by modification of non-symbolic operators. Both kinds of operators can be investigated by their signs of neuroelectric activity. I propose that the postulated differences should be sought by classification of the spatial textures of the signs in EEG recorded from the scalp overlying those cortical structures unique to humans in the brain that I designate as koniocortex, while the subjects are engaged in elementary arithmetic operations.

1. Introduction

Comprehension of the origin and nature of natural computing by brains is to be sought through understanding the neurodynamics of intentionality in animals. The dynamics of interactive neurons in the brain thrusts the body into the environment with the intent to manipulate an object or event or to orient the senses with respect to an object or event.

Each act of observation intends the gathering of information concerning the status of the brain and body with respect to expected possible future states. Those states are predicted from the context of experience embodied in synaptic networks constituting memory and knowledge, and the present relations that hold in the dynamic states of brain and body constituting selective attention. This process is known as the action-perception cycle [Merleau-Ponty, 1942]. It is the mechanism by which brains solve the symbol grounding problem by assimilation of their experience in exploring their environments and changing themselves to conform to what they find.

The salient characteristic of intentionality, as conceived by its originator Aquinas [1272] and more recent commentators Heidegger [1972], Merleau-Ponty [1942] and Dreyfus [2007], is that the brain is an open system with respect to energy and information but a closed system with respect to meaning. Its unity is inviolate. It can predict the form of an object or event and test its predictions, but the macroscopic form and information content of an object or event are not transferred through the microscopic sensory receptors and pathways into the brain. The intentional act of observation anticipates a collection of possible outcomes of the sensory consequences of each action. These expectations are actualized from moment to moment from the global knowledge base in cortex by a neural process termed preafference [Kay and Freeman, 2001]. Preafference is revealed in the selective sensitivity of the aroused sensory cortices to sensory input that is relevant to the prevailing situation. It denotes the process by which the limbic system selectively activates an array of pre-existing synaptic networks of neurons that embody some part of knowledge in the brain (a collection of memories) that is made topical by the intent of forthcoming observations, and that is realized in the selection and activation of one among a collection of nerve cell assemblies controlling access to attractors in landscapes [Skarda and Freeman, 1987].

The act itself requires positioning of the entire array of sensory receptors in the several modalities with respect to the intended object or event by manipulation of the body constituting "maximum grip" [Dreyfus, 2007]. The consequences of the act are the selection of one of the predicted outcomes, and the updating of the selected cortical synaptic network in the brain. The updating of the network accommodates to the environment by incorporating the differences between expected and actual microscopic sensory inputs. The cumulative changes in cortical networks continually expand and adapt the knowledge base in the brain.

2. The operators of natural computing form categories under intention.

The prototypic elements of natural computation by intention are the identified categories of objects and relations that are defined by the synaptic networks in the brain, because they embody the memories shaped by learning from past encounters with the objects in the environment. Each such category relies on a Hebbian nerve cell network. The connections within the network are strengthened in association by correlated firing under reinforcement. The connections from neurons outside the network are weakened by habituation in the absence of reinforcement. The network is the key to access a nonconvergent (chaotic) attractor that regulates a spatiotemporal pattern of cortical activity. A collection of attractors that is actualized by preafference from the knowledge base in the anticipatory stage of an act of observation forms an attractor landscape, which itself is an attractor in a hierarchy of nested landscapes.

Each category exists only in the brain. It has both form and function. The enduring structure is the microscopic strengthening and weakening of synapses forming and insulating a nerve cell network, which can be regarded as a cumulative correlation map of the microscopic sensory input from co-activated sensory receptors under reinforcement. The transient activity guided by the attractor results from selection of the basin of the attractor by the input. The basin of attraction is defined by the cumulative set of coactivated sensory receptors on all past experiences. The process constitutes inductive logic: forming a category by repeated sampling in many-to-one convergent dynamics. The categories are inferred to correspond to forms that exist in the environment. Those inferences are based on success in achieving repeated correspondence between expectation and realization of microscopic sensory input, that is, confirmation of hypotheses with the achievement of neurochemically mediated reinforcement.

Because natural computation is intentional, we can begin to define its neural basis. Specifically, the categories constituting its operators are stable and enduring in their anatomical synaptic networks, yet highly fluid in their activations leading to driving and modulatory actions on neural populations in cortex, whether immediately or remotely derived from sensory input. The categories exist only in the brain as abstractions and generalizations. They are to be sought in large-scale neural structure and activity having low spatial density and wide correlation length. They are mesoscopic patterns that differ markedly from microscopic sensory and neural activity patterns, which are spatially localized at high density in small clusters of neurons. Microscopic activity driven by sensory input cannot be part of the knowledge base because it is unique and ephemeral; knowledge in the form of interrelated categories is enduring yet continually changing over the lifespan of the brain and body. An analogy to the mesoscopic-microscopic distinction that is often used is the difference between statistical mechanical vs. thermodynamical descriptions of matter, but this analogy is misleading, because unlike molecules every neuron is unique and changing.

3. The elementary operators of natural computing are digits, i.e., fingers and toes.

The implementation of intentional actions necessarily employs the body. This is obvious for natural computing in the foundations of arithmetic. The widespread usage among humans of the decimal base for enumeration stems from a product of vertebrate evolution: the five fingers and toes on each limb. The neurobiological assignment of this function to the human cortex is supported by the uncommon but well documented consequences of a lesion in the right parietal lobe first described by Gerstmann [1958] as the syndrome of inability to distinguish left from right; difficulty in writing (agraphia); failure to perform simple arithmetic operations (dyscalculia); and inability to name the fingers: thumb, index, middle, ring and pinkie (finger agnosia).

There is more. The index finger serves as the agency for communication among observers of the category and location of an object or event. Infants who first learn to point invariably look to their mothers to get confirmation of shared fixation of gaze in observation. The hands are the agencies for selecting and accumulating objects of like kind, in accord with the categories that are predicted through preafference, and among which one is selected by the sensory input from each act of observation. The hand is the prime agency for symbolic representation. The index finger is the symbol for one. The clasp of hands is the symbol for unity. It is primarily through the hands that flow the execution of patterns created within the brain from stable networks. A venerable example is the cursive signature that legally signifies the person's intent: it is never twice identical, showing that each execution is a novel creation guided by some nerve cell assembly and its accompanying attractor, that is, a neural category, yet it is easily recognized, whether written with the customary or the opposite hand, or the jaw or toes holding the pen, showing that its assembly is not in the neurons controlling the hand.

In acquiring the capacity for natural computing the body is essential to the brain [Lakoff and Núñez, 2000]. Addition is implicit in making a pile of nuts. Subtraction is implicit in separating it into smaller piles. Multiplication and division are seen in the making of piles and then sub-piles of equal size. Geometric relations are likewise executed by movements of the body, as in using a vine or rope to make a straight line, and tying 12 knots in the rope to measure distance, and arranging it in a 3-4-5 triangle to make a square, and using a compass to make a circle. More generally Henri Poincaré in his Dernières Pensées [1913] asked the question: "Why do we see in 3-D?" His answer: because we move in 3-D. The mapping of numbers into Cartesian coordinates clearly demonstrates the co-dependence of arithmetic and geometry on categories of numbers. The intentional capacity of humans to move through space rhythmically in time at countable intervals and steps introduces us to the elements of arithmetic.

4. Venturing into the unknown: neural operators and their observable signs.

The actions of the body manifest directly the foundations of natural computation in the neural operations of the action-perception cycle of intentionality [Merleau-Ponty, 1942]. We can assert with confidence that the categories and operations constituting symbols and symbol manipulation of natural computing require spatiotemporal patterning of neural activity as the basis for creating and manipulating symbols. Physiologists now have capabilities for observing some neural correlates of these operations at three main levels of observation: microscopic recording the trains of action potentials emitted by axons of single cells, the mesoscopic recording of the local field potentials generated by the dendrites of neural populations (the electrocorticogram, ECoG), and noninvasive macroscopic recording of the electric and magnetic fields of potential at the scalp (the electroencephalogram, EEG, the magnetoencephalogram, MEG, and hemodynamic images of brain metabolic processes that support dendritic currents. The question is: How might we use such recordings to explore the neural mechanism of natural computing in the neurodynamics of brains?

An intrinsic difficulty with the proposed approach is that construction of a symbol is an intentional act. How does the act differ from an intentional non-symbolic act? For example, the deliberate twitch of one eyelid in a wink may be an attempt to relieve a dry eye, or it may be a symbolic gesture to invite intimacy with a prospective sexual partner. A more dramatic example is provided by the editor and essayist J-D Bauby, who wrote an entire book despite being paralyzed in the locked-in syndrome with the sole exception of his left eyelid [Bauby, 1997]. As his caretaker recited the alphabet with letters ordered in frequency of usage in French, he winked at the letter he intended. It is the context in which the intentional action is organized and performed that enables the necessary distinction, and that must be captured and used in discovering the nature of the difference in neural activity between a symbolic pattern and non-symbolic pattern.

The step that we cannot take yet is to advance beyond the signs giving immediate neural correlates of actions and perceptions by the body. That step is most starkly posed by considering the most dramatic contribution to mathematics of the past two thousand years: the invention of zero. What is the step in brain dynamics that goes beyond categorizing inputs from a collection of objects or events in creating a *symbol* of a category that has no objects or events? How in both experimental and mathematical terms can we define and describe the particular operation or class of operations by which the brain constructs a symbol and then uses it to reach intended goals?

We can straight-forwardly establish experimentally the neural correlates, that is, the signs of activity that accompany presentation of an object. The approach to establishing the neural correlate of an object that does not exist or of an empty set presents an opportunity to breach this barrier to the unknown. Ichiro Tsuda [2008] poses the issue by showing how numbers arise as categories by preafference in the action-perception cycle expressing intent in the activation of memory, beginning with the natural numbers for groups and extending the process to creating the number zero from one. He then appeals to brains' chaotic dynamics for the generation of real numbers, showing the power of this approach.

The issue is not how to model dynamical and logical systems mathematically; it is how to describe the operators created by masses of neurons that direct the body to construct and manipulate symbols that are grounded in the environment by intentional action. We postulate that they have the generic form of spatiotemporal patterns of neural activity that are closely related to the patterns of neural activity that support and mediate the action-perception cycle in non-symbolic action. This generic form is the synchronized oscillation of the dendritic current and pulse densities of populations of neurons [Freeman, 2004-6]. The phase locking of the oscillation is in a narrow spectral band for each perceptual event, but the center frequency varies widely in successive events. The shared power is a small fraction (~0.1%) of the total variance of the population activity. The event is located in an area of cortex with a soft boundary corresponding to the half power radius of the shared variance. The event has a sudden onset by a phase transition marked by a discontinuity in the oscillatory signal, and it terminates by gradual desynchronization demarcating a temporal frame [Freeman, 2007]. The frame repetition intervals and rates are manifested in the low frequency ranges of the ECoG, EEG and MEG. The contents of the frames constituting the activated portion of the knowledge base are expressed in the spatial patterns of amplitude modulation (AM) of the narrow band carrier wave of the oscillation.

The human AM patterns that serve as neural operators for symbol construction (let us call them AMH patterns) are expected to differ in two aspects from the AM patterns that implement the non-symbolic actions. One aspect is that AMH patterns cannot be directly involved with implementation of motor-sensory-perceptual processes, as are the more concrete activity designated as AM patterns. The other aspect is that AMH patterns provide the operators for logic and arithmetic, and it is those operations and the signs of AMH patterns that collectively constitute the target for neurobiological research in natural computation. At the most basic level of description, the AMH patterns may be close kin to and perhaps indistinguishable from the elements of natural language, that is, the neural commands that produce spoken or written words. The central hypothesis of this essay is that natural computation emerges and evolves from intentional action, whether or not it is comparable to language and metaphor [Lakoff and Núñez, 2000]. The development is unique to humans beyond the most rudimentary capabilities for subsymbolic operations in non-human species. Therefore, natural computing must be related to some unique structures and functions human neocortex. The proposed search is not for "modules" or "centers" for geometry and arithmetic but for collections of neurons that enable and facilitate the emergence of some as yet undefined heirarchical levels of organization in brain dynamics, beyond the micro-meso-macro designations that hold for operations in human and animal brains that support the action-perception cycle.

An obvious location in which to concentrate the search for AMH pattern signs is in the convexities of the frontal, parietal and temporal lobes. The study of fossil endocasts has shown that these parts of the human brain in the past half million years have evolved in size faster than any other organ in any other species ever. Moreover, in all non-human species every area of neocortex is in direct synaptic communication with underlying neural populations in the brain stem and basal ganglia, particularly the thalamus and the striatum, but in the human brain there are cortical areas that lack such pathways for direct neural communication. Yakovlev [1952, 1962, 1970] who first described this isolation proposed that the relative insulation provided the synaptic distance from pinning to the environment that was required for the emergence in humans of the capacity for symbolic operations. These areas may correspond to "koniocortex" (from the Greek 'konios' meaning 'dust'), a term used by anatomists to describe areas of human cortex having innumerable cells with no distinguishing architectural features, suggesting an all-purpose type of cortex. However, the koniocortices having a remarkable degree of distance from sensorimotor areas should not be conceived as modules for computing but as facilitators for the higher-order organization of very wide synchronization of cerebral activity. Synchronized beta and gamma oscillations have now been identified with correlation distances approaching and exceeding 20 cm, more than half the distance across the length of each hemisphere in EEG [Freeman et al., 2003] and MEG [Bassett et al., 2006]. It is the textures in AM and AMH patterns in these frames of activity that should be targets for recovery and analysis.

The implication is two-fold. First, if one wishes to discover the neural principles of natural computation, one must study the neural signs of the process in humans engaged in computation. Second, the neural structures of chief interest are those lacking thalamic and striatal direct connections, which are traditionally regarded as 'associational'. The most favorable circumstance in this endeavor is that the cortical areas in question are probably located in parts of the neocortex that are rather favorable for recording neural correlates in the scalp EEG over the calvarium (the dome of the skull), particularly in proximity to the speech areas of Broca and Wernicke, and the motor, premotor, and parietal areas that control the digits of the hand. Computationalists will have to call on neuroanatomists to review and catalog the locations of cortical areas lacking direct subcortical connections. That intrinsically is a daunting task, because for each area it requires demonstration of connections that do not exist. Such areas are likely to have other distinctive functional and structural properties. A comparable evolutionary difference is seen in the contrast between the three-layered allocortex of reptiles, mainly in the olfactory and hippocampal systems, and the six-layered neocortex of mammals, the latter being far more powerful in several aspects [Freeman, et al., 2008]. Just so, the symbol-generating cortices may require as yet unknown neurodynamical properties. Hence I suggest using the histological term *koniocortex*.

5. How might we approach the mathematical descriptions of AMH patterns and operations by and on them?

The technical details of the requisite physiological search lie outside the scope of this essay established [Viana Di Prisco. Freeman, 1985; Barrie, Freeman and Lenhart, 1996]. The prototype for category learning has been by recording the auditory cortical ECoG of Mongolian gerbils [Ohl, Scheich and Freeman, 2001]. I emphasize that remarkable as is the achievement of this result and insight, the gerbil AM patterns relating to FM tones as presently understood do not have the status of symbols. They lack the flexibility of instant reassignment and participation in multiple types of behaviors. Again I emphasize that the neural mechanisms of intentional actions in natural computing that are to be modeled are representational rather than directly enactive and adaptive. An experimentalist might begin by presenting objects to human subjects of different kinds in groups of zero, one, two, three or four in order to search for and identify AMS patterns in brain waves that correspond to these categories not as concrete items such as fruit or utensils (as would AM patterns) but as abstract categories of numbers, and then, having done so, request subjects to perform the basic arithmetic operations by which these concepts are related through transformations. The assistance of students engaged in learning arithmetic and especially their teachers will be invaluable. In particular, can experimentalist identify an AMS pattern correlated with the concept of zero? How might they change when a subject adds the symbol for zero to the symbol for three and gets the symbol for three, as opposed to subtracting one and getting two?

In keeping with the premise of this essay, the identification and verification of the signs of AMS patterns will require induction of the action-perception cycle, while recording the behavior and the brain waves of the subjects. Comparably, simulation of the process by a 'natural computer' would have to be done with an intentional robot [Kozma et al., 2005; Kozma et al., 2007; Puljic and Kozma, 2008] that will implement its action-perception cycle in testing the effectiveness of its own natural computations. There is no other way to solve the symbol grounding problem in simulations than to capitalize on the knowledge base that an intentional robot accrues from its own trial-and-error experience by acting into its world. Presumably it might be hoped that the device will advance beyond counting on its equivalent fingers; however, that is a stage that it and we must achieve before advancing from actions into symbolic representations.

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The assistance of physicists will be equally essential in describing and simulating the transformations in neural activity that might be consistent with the neural operations deduced from the neural signs. The most important operation is the phase transition by which AM patterns form [Kozma et al., 2005; Freeman, 2008]. This event involves a discontinuity in the analytic signal derived from brain wave recordings, which ushers in a new AM pattern and a new phase pattern having the form of a radially symmetric conic gradient in the phase of the carrier frequency [Freeman, 2004-6]. It is to be expected that symmetry breaking and the reassertion of symmetry [Freeman and Vitiello, 2006; Freeman et al., 2008] will play prominent roles in forming and dissolving neural categories, beginning with steps going from zero to one and then to two. It is likely that the neural phase transition, which is so important in perception and decision, will play prominent roles in the operations performed by and on AMS patterns.

There are attractive possibilities for conceiving and demonstrating complex topological changes in attractor landscapes in the insulated neocortices that accompany performance of the most elemental arithmetic operations. The necessary multisensory arrays and multichannel data processors are already available commercially for collecting the data noninvasively from trained human subjects. We now have a powerful array of mathematical techniques, including from my own experience linear and nonlinear neurodynamics [Freeman, 1975], far-from-equilibrium thermodynamics [Freeman, 2007], dissipative quantum field theory [Vitiello, 2001; Freeman and Vitiello, 2006], renormalization group theory [Freeman and Cao, 2008], and neuropercolation [Kozma et al., 2005]. Reports using these and comparable formal treatments will grace the pages of this journal. Indeed this is the best of times to open this new continent for exploration with the mathematical and technical tools that seem extraordinarily complex and advanced from our present perspective, but which will appear to our descendents as quaint, in the way that we now see in museums the brass microscopes and telescopes that supported the collection of the knowledge that we now enjoy and project into our own futures.

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