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Bridging the Gaps Between Neuron, Brain and Behavior with Neurodynamics

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Abstract

Brain systems operate on many levels of organization, each with its own scales of time and space. Dynamics is applicable to every level, from the atomic to the molecular, and from macromolecular organelles to the neurons into which they are incorporated. In turn the neurons form populations; they form systems, and so on to an embodied brain interacting intentionally with its environment. Each level is "macroscopic" to the one below it and "microscopic" to the one above it. Among the most difficult tasks are those of conceiving and describing the exchanges between levels, seeing that the scales of time and distance are incommensurate, and that causal inference is far more ambiguous between than within levels. That holds for the relation of action potentials from microelectrodes to whole brain activity seen with new techniques for brain imaging: fMRI and PET. A new recourse is to conceive, identify and model an intervening "mesoscopic" level, which is a local self-organizing neural population. Its characteristic activities consist of 'spontaneous' action potentials and EEG dendritic activity. Mesoscopic neurodynamics gives a clear understanding of self-organized chaotic patterns of neural activity in primary sensory areas when significant stimuli arrive. These patterns are created with each sniff, glance, or movement of the head and hands. They are triggered by sensory input, but they are not the result of information processing, and they are not representations of stimuli. They are manifestations of the way in which brains make and test hypotheses. The patterns show that brains do not take information into themselves. They formulate expectations as hypotheses and test them by taking action into the environment. They are not data-driven; they are hypothesis-driven, and all that they can know is what

hypotheses were tested, and what the results of the tests were.

Freeman WJ (2001) *How Brains Make Up Their Minds*. New York: Columbia University Press.

Introduction

"Why on earth should a cause turn an action into a mere happening and a person into a helpless victim? Is it because we tend to assume, at least in the arena of action, that a cause demands a causer, agency and agent? So we press the question; if my action is caused, what caused it? If I did, then there is the absurdity of an infinite regress; if I did not, I am a victim. But of course the alternatives are not exhaustive. Some causes have no agents. Among these agentless causes are the states and changes of state in persons which, because they are reasons as well as causes, constitute certain events free and intentional actions." (Davidson 1980, p. 19)

What is consciousness? It is known through its manifestations of the activities in living brains in living bodies. In this respect whether it arises from the soul (Eccles 1994), or from pan-psychic properties of material events (Whitehead 1938; Penrose 1994; Chalmers 1996), or as a product of brain operations (Searle 1992; Dennett 1991; Crick 1994) is not relevant. The pertinent questions are - however it comes into play before or after birth - how is it related to nonlinear brain dynamics? In what senses does it cause the functions of brains and bodies, and how do brain and body functions cause it? The forms of answers depend on the choice among meanings that are assigned to "cause" [verb]: (a) to explain, rationalize and blame [reason]; (b) to make, move and

modulate [agency]; or (c) to flow in parallel as a meaningful experience, apparition, or epiphenomenon, which reduces causality to an invariant concomitance [dualism]. Therefore analysis of causality is a necessary step toward comprehending consciousness, and dynamics gives us the framework in which to construct the analysis.

The structures and activities of brains and bodies are comparable in many respects over a broad variety of animals. My hypothesis is that some of the elementary properties of consciousness are manifested in even the simplest, and that its complexity increases with the evolution of brains into the higher mammals. I summarize my understanding of the structure and dynamics of simpler brains and then explore how causality might be conceived in conjunction with the neural operations that relate to behaviors of humans. I sketch the neurodynamics of a prototypical sensory system of the brain, the ways in which it is controlled by the forebrain in the mechanisms of attention, the development of the system through bifurcations during learning, the formation of meaningful classes of input by generalization, their access by state transitions, and the role of chaos in constructing new attractors in cerebral cortex as the basis for consciousness.

Neural Activity in the Forebrain as seen in the EEG

This property of chaos is not readily apparent in the nonlinear regulatory feedback mechanisms of brain reflexes, which insure the stability of brain function by keeping the internal environment of the brain at an optimal level, a process called homeostasis, but it becomes clear in modeling perception, which is a creative interaction with the external environment. An example comes from study of the neural activity in the olfactory bulb, and the visual, auditory and somatosensory cortices. These are semi-autonomous systems that interact with other parts of the forebrain by both transmitting information and receiving regulatory feedback. Their basic functions are self-organizing. Their chaotic activity is a global property that arises from the synaptic interactions of millions of neurons. This is important, because the patterns that are

recognized in perception are characterized by relationships between each part and every other part of the patterns.

The clearest demonstrations of the self-organization of complex spatiotemporal patterns of neural activity are presently found in simultaneous recordings of EEG activity from arrays of 16-64 electrodes placed on the sensory cortices of rabbits. In each case the recordings reveal a common oscillation in cortical potential over the entire array (Freeman 1991). The oscillation serves as a carrier wave for perceptual information in its spatial pattern of amplitude modulation. The wave form of the carrier is aperiodic and unpredictable, reflecting the chaotic dynamics of sensory cortices. The spatial patterns of amplitude do not literally represent the stimuli that are transmitted to the cortices over their sensory input pathways. They reveal instead the experiential content that has been associated with stimuli during periods of training to respond to them, in brief, the "meanings" of the stimuli for the subjects. This holds for all sensory cortices.

When observed during time spans of minutes to hours, the dynamic mechanisms appear to be robustly stable over a wide range of amplitudes. They can also be destabilized by neurochemical modulatory input from other parts of the brain, which can close them down, as with transition to the stable state of sleep, and with learning to identify a new class of input. These and related phenomena emphasize the role in neurodynamics of regulatory biases from other parts of the brain onto self-exciting populations in neural system control. Most importantly, learning takes place in rapidly repeated small steps, which cumulatively give the appearance a trajectory in state space that never repeats itself. This is a manifestation of Tsuda's (1996) "chaotic itinerancy". It underlies the phenomenon of perceptual drift by which imperceptible modifications occur in the outlook of people adapting to changing environments.

The Role of Refference in Attention

A key concept in models of perception and motor control is that of refference (Kay and Freeman 1998). When a brain activity pattern that is generated by chaotic dynamics expresses

a drive toward a goal, it has two facets. One is a motor command that activates the descending motor systems. The other is a set of messages to all of the central sensory systems, that prepares them for the impending changes in sensory input that will be caused by the motor action. Studies with in vertebrate evolution (Herrick 1948) and experimental surgery (Freeman 2000) have shown that these neural activity patterns emerge in the limbic system, a network of cortex and subcortical nuclei in the forebrain. As the limbic system initiates action into the world, its reafferent messages ("corollary discharges") prepare the sensory cortices to accept the sensory consequences of those actions by shaping their attractor landscapes. The sensory consequences of behavior together with evolving sensory input, such as the retinal images that change from searching movements of the eyes while tracking a moving target, are fed back into the limbic system. Multimodal perceptual convergence takes place through the entorhinal cortex and hippocampus, structures that are inferred to be essential for the maintenance of the cognitive map (spatial orientation) and of short-term memory (temporal orientation).

State Transitions during Perception

The output of each sensory cortex is a spatial pattern of amplitude modulation of the common wave form of the oscillation, which expresses the cooperative interactions of all of the bulbar neurons. This output is carried in parallel by millions of axons that transmit to the cortical targets. The pathways diverge, in that each local area of the cortex transmits broadly to the neurons in its target. Correspondingly, each local area in the targets sums the activity that it receives. By virtue of this spatial integration the only activity that is enhanced is that which has the same frequency of oscillation everywhere. This is the cooperative activity that is the "signal" of the cortex. The local activities in the cortex that result from sensory input, and which are the "raw sense data", are smoothed and deleted as "noise" by the summation acting as a low pass spatial filter. In this way the cortex transmits its own created pattern and not the imprint on its activity of the sensory input.

The reason for this process is that the sensory environment is infinitely complex, and the

neural mechanism for stimulus classification is finite. The same codes and modes of operation hold in the olfactory, visual, auditory, and somatosensory cortices (Barrie, Freeman and Lenhart 1996). My conclusion is that brains can only know what has been constructed by their sensory cortices under their control and guidance (Freeman 1991).

The formation of a nerve cell assembly during training therefore involves modification of synaptic strengths, which are simulated by increasing the values of the appropriate excitatory feedback gains. Learning takes place by a structural change in the system, such that its behavior in the future is dependent on past experience. In this respect the learning process is similar to the induction of epilepsy and to changes between sleeping and waking states, which are done by parametric modifications supporting the sudden state transitions called bifurcations.

The state transition between basal and burst states does not involve a parameter change. It depends on input. Therefore, this change is not a bifurcation. One way to view the operation of responding to input is to postulate that each sensory cortex has a global attractor landscape that has multiple basins of attraction, one for each class of input that it can discriminate. The system is forced out of the basal state by receptor input with each sensory input, and if it contains a known stimulus, the cortex is constrained to oscillate in one of the basins of attraction, which provides for the generalization gradient in classifying repeated stimuli that are never twice the same in detail.

Self, Awareness of Self, and the Illusion of Control

In viewing the problem of the self from a biological perspective, two facets of self can be distinguished. One is the public facet that is constituted by brain dynamics, that controls observed behavior. The other is the private facet that is based in awareness constituting personal experience. These two facets bond in the process of perception, by which global patterns of brain activity come briefly into focus at a point in a trajectory, collecting all the

residues of past experience, and influencing by embedding transmissions all that is to come in the life span of an individual.

Empiricists (materialists) and idealists (cognitive scientists) commonly view perception as a late stage of a process that begins with sensory transduction to form representations of stimuli, commonly in the firings of feature detector neurons. They hold that it proceeds through "binding" of the parallel activity of multiple feature detectors through summing by higher-order neurons to represent objects, so-called 'grandmother neurons', and then by the serial processes of filtering, normalizing, matching with representations retrieved from storage for pattern completion and classification. Perception is completed upon the binding of the representations of an object from the multiple sensory systems, after an appropriate value or meaning is attached to the fused image.

The studies of brain activity during perception by animals trained to discriminate olfactory, visual, auditory, or tactile stimuli (Freeman 1975, 1992, 2001) have led to an alternative view, in which a percept is a goal-directed action that is organized by large scale neural interactions in the limbic system. Such action is intentional, in that it forms within a framework of space and time that has been constructed from recent and remote experiences of action and its sequellae, and it constitutes "stretching forth" into the world, in order to shape the self in accordance with what is there.

Brain scientists have known for over a century that the necessary and sufficient part of the vertebrate brain to sustain minimal intentional behavior, a subclass of intentionality, 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 of the newer parts of the forebrain have been surgically removed (Goltz 1892) or chemically inactivated by spreading depression (Bures, Buresová and Krivánek 1974). Intentional behavior is severely altered or disappears following major damage to the basal

forebrain. Phylogenetic evidence comes from observing intentional behavior in salamanders, which have the simplest of the existing vertebrate forebrains (Herrick 1948).

Neurosurgeons have shown that the frontal lobes are especially important for complex intentional behavior. The orbitomedial frontal cortex has very strong interactions with the temporal parts of the limbic system through the uncinate tract, and damage to that part of the frontal lobes is followed by severe impairment of the ability of patients to experience and express emotions, and to engage in satisfactory social behavior. However, intentional behavior is still present, even though it is greatly impoverished, and the patients are "socially blinded". Damage to the anterior temporal lobes, which contains a substantial part but not all of the limbic system, results in severe loss of spatial and temporal orientation (short term memory) and wholeness, which is manifested by an inability to continue constructing and remembering a life history. I argue here that the adaptiveness and flexibility of intent, the fullness of life-long memory in wholeness, and the cognitive content of meaning in "aboutness" are elaborated by the chaotic dynamics of neocortex, and that these three aspects are inextricably linked in the limbic system.

The motor 'commands' that issue through the septum and amygdala are accompanied by refferent 'corollary discharges' (Kay and Freeman 1998) sent by the limbic system to all of the sensory cortices, which constitute attention by shaping the dynamic sensitivities of the cortices, in respect to the anticipated changes in sensory inflow that will follow the intended actions. Thus the sensory systems are already primed to respond in selective ways to the stimuli that are being sought through listening, looking, sniffing, etc. Closure of the action-perception cycle takes place following the de-stabilization of the sensory cortices, their construction by nonlinear dynamic interactions of spatial patterns of activity, the convergence of these patterns into the limbic system, whence issued the request for input, and finally the updating of the limbic activity.

This mode of brain function was put forth by the American pragmatists, most clearly by John Dewey (1914) in his critiques of the

conditioned reflex. It was further developed by Gestalt psychologists (Köhler 1940), who studied the impact on perception of objects embedded in environmental contexts, leading to the conception of a field of force, which resonates with brain dynamics. Koffka (1955) expanded this concept to include interaction between fields of force in the environment and in the brain. Gibson (1979) further conceived the role of behavior that is generated within brains in the definition of objects by means of affordances. In his conception, "information" derives from objects in the world and is incorporated by resonance of Gestaltist fields to "in-form" the brain. This is closely related to the "intentional arc" of Merleau-Ponty (1942, 1945), but with the difference that an affordance constitutes information in an object, and the resonance transfers that information into the meaning, whereas in the existentialist view, the intentional brain state defines the object in term of an emergent goal with its unity of inner context, and there is no transfer of information, only a modification of the self as the result of action. The Gestaltist and Gibsonian approaches are essentially passive, by virtue of the source of organization being attributed to objects and events in the world, whereas the existential approach attributes the structure of behavior to active self-organizing dynamics in brains leading to hypothesis-testing.

The critical link between the public and private facets occurs at the moment of up-dating of the limbic pattern of activity, which incorporates the immediate result as a fresh small step along a trajectory extending into the future. The formulation of the next succeeding step is shaped by the entire body of past experience at play with each step, including the projection from the past into the presently existing threads extending into the future. With all its limitations of perspective and short-field emphasis, this field of activity is the basis for decisions and choices, and for the awareness of that field, which is consciousness. One key limitation is that time is required for neurodynamics to construct and reorganize the dynamic patterns following each definable stimulus. Libet (1994) has shown that there is a delay of 0.5 sec between the arrival of a stimulus and the onset of awareness of the stimulus, following the P300, though that onset is subjectively back-dated to the actual time of

arrival. Popper and Eccles (1977) thought 'back-dating' had no physiological explanation. However, the process is analogous to the two-threshold technique in common use by physiological psychologists for identifying *that* a response has occurred with a high threshold, and detecting *when* it occurred with a preceding low threshold. Libet (1994) has extended his studies to the decision process using the well-known scalp-recorded CNV (contingent negative variation), which shows that similar delays occur in the emergence of awareness of actions.

Conclusions

In these terms, the intentional, dynamic, public, limbic self continually constructs the neural activity patterns that seek sensory input. The global updating that sets the matrix for each next step lags by half a second. Both the initiating actions and the arrival of sense data de-stabilize cortices and initiate fresh constructions. In this view the private experiential awareness of self, the "ego", is invariably half a second behind, always justifying, explaining, rationalizing, and claiming credit by virtue of the capacity to back-date, which was designed by evolution of the mammalian neocortical sensory system to provide a mechanism for keeping the foundational self in near synchrony with the unfolding real world. This is the reverse of the view of Descartes, whose vaunting ego got it backwards. The existentialist says, "I am, therefore I think". Mahayana Buddhists and Lacanian psychoanalysts have written alike about the "illusion of the self". In the intentional view the illusion is not of the existence of the ego, but of the ego as being in control of the self.

The intentional self can also be called the social self, because it is the organizer of observed action and the locus of assignment of responsibility for action. It cannot be divided, except, according to Sperry (1982), by splitting the brain, in contrast to the commonly splintered and bickering fragments of the private facet of the awareness of self. Thus consciousness is neither caused by nor a cause of behavior (in the sense of agency), nor is it an experiential aspect of matter in the dualist sense proposed by Whitehead (1938), Penrose

(1994), and Chalmers (1996). It is the subjective aspect of the context in which the limbic mechanisms of intentionality construct the patterns of neural activity that are observed as behavior, and that are inferred to exist in situations that involve social interactions. It is the remembrance of the past, the quale of the present, and the forecast of the future, in which the decisions are made by the self concerning what to do next, prior to awareness, at each moment of an unfolding life span. It is a rational explanation. Since everything that we know is derived through the action-perception cycle, which we experience as cause-effect, it is natural for us humans to endow objects and events in the world with agency, just as our ancestors attributed spirits to the parts of the world with which they dealt.

References

- Amari S (1977) Neural theory of association and concept formation. *Biological Cybernetics* 26: 175-185.
- Anderson JA, Silverstein JW, Ritz SR, Jones RS (1977) Distinctive features, categorical perception, and probability learning: Some applications of a neural model. *Psychological Review* 84: 413-451.
- Barrie JM, Freeman WJ, Lenhart M (1996) Modulation by discriminative training of spatial patterns of gamma EEG amplitude and phase in neocortex of rabbits. *Journal of Neurophysiology* 76: 520-539.
- Bures J, Buresová O, Krivánek J (1974) The Mechanism and Applications of Leão's Spreading Depression of Electroencephalographic Activity. New York: Academic Press.
- Chalmers DJ (1996) The Conscious Mind. In Search of a Fundamental Theory. New York: Oxford University.
- Crick F (1994) The Astonishing Hypothesis: The Scientific Search for the Soul. New York: Scribner.
- Dennett DH (1991) *Consciousness Explained*. Boston: Little, Brown.
- Davidson D (1980) Actions, reasons, and causes. In: *Essays on Actions & Events*. Oxford UK: Clarendon Press.
- Dewey J (1914) Psychological doctrine in philosophical teaching. *Journal of Philosophy* 11: 505-512.
- Freeman WJ (1975) *Mass Action in the Nervous System*. New York: Academic Press.
- Freeman WJ (1991) The physiology of perception. *Scientific American* 264: 78-85.
- Freeman WJ (1992) Tutorial in Neurobiology: From Single Neurons to Brain Chaos. *International Journal of Bifurcation and Chaos* 2: 451-482.
- Freeman WJ (1995) *Societies of Brains. A Study in the Neuroscience of Love and Hate*. Mahwah NJ: Lawrence Erlbaum Associates.
- Gibson JJ (1979) *The Ecological Approach to Visual Perception*. Boston: Houghton Mifflin.
- Goltz FL (1892) Der Hund ohne Grosshirn. *Pflügers Archiv* 51: 570-614.
- Herrick CJ (1948) *The Brain of the Tiger Salamander*. Chicago IL: University of Chicago Press.
- Kay LM, Freeman WJ (1998) Bidirectional processing in the olfactory-limbic axis during olfactory behavior. *Behavioral Neuroscience* 112: 541-553.
- Koffka K (1935) *Principles of Gestalt Psychology*. New York: Harcourt Brace.
- Köhler W (1940) *Dynamics in Psychology*. New York: Grove Press.
- Libet B (1994) *Neurophysiology of Consciousness: Selected Papers and New Essays*. Boston MA: Birkhauser.
- Merleau-Ponty M (1942/1963) *The Structure of Behavior* (Fischer AL, Trans.). Boston: Beacon Press.
- Merleau-Ponty M (1945/1962) *Phenomenology of Perception* (Smith C, Trans.). New York: Humanities Press.
- Penrose R (1994) *Shadows of the Mind*. Oxford UK: Oxford University Press.
- Popper KR, Eccles JC (1977) *The Self and Its Brain*. Berlin: Springer-Verlag.
- Searle JR (1992) *The Rediscovery of Mind*. Cambridge MA: MIT Press.
- Skarda CA, Freeman WJ (1987) How brains make chaos in order to make sense of the world. *Behavioral and Brain Sciences* 10: 161-195.
- Sperry RW (1982) Some effects of disconnecting the cerebral hemispheres [Nobel Lecture]. *Science* 217: 1223-1226.
- Tsuda I (1996) A new type of self-organization associated with chaotic dynamics in neural networks. *International Journal of Neural Systems* 7: 451-459.
- Whitehead AN (1938) *Modes of Thought*. New York: Macmillan.