

**Brain Dynamics: Brain Chaos and Intentionality**

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The search for an understanding of how human beings create themselves through their actions arising in their brains inevitably leads to the study of chaos. Deterministic chaos is characterized by complexity that is self-organized in accordance with simple underlying rules. Examples are found at all levels of organization of nervous systems. The search for simple rules is one good reason for using the tools of the theory of chaos to model neural functions. The appropriate level for researchers who are interested in perception, cognition and consciousness is the level of macroscopic neural populations, because in animals from insects to man, that is where the organization of perception and goal-directed behavior with respect to the external environment occurs. The dynamics of these populations is shaped by learning from the sensory consequences of intentional actions, and it uses chaotic attractors in the cerebral cortex to provide the background, "spontaneous" activity that is required for the creation of novel trials in trial-and-error learning. Humans learn by, in and through chaos, and the global dynamical structure of the neural populations constitutes the self.

**Chaotic Dynamic Brain Function**

The biology of human brains should be approached first and foremost in terms of how they construct intentional behavior, while enabling humans to know what they are doing, and why. The theory of nonlinear dynamics has greatly expanded our understanding of neural mechanisms by which large-scale patterns of brain activity are self-organized. The new concepts give us fresh insight into the neurodynamics of intentional behavior, how consciousness emerges within the brain, and how brains regulate their own sensory inflow into the cortex (Freeman 1995). The classical stimulus-response paradigm in psychology clearly fails to address the most basic properties of biological intelligence and control, which are its autonomy and its creative powers. Chaotic dynamic systems not only destroy information, they also create it. In previous work (Freeman, 1991) a number of aspects of local field potentials from summed dendritic synaptic potentials (electroencephalograms, "EEGs") and axonal action potentials (nerve impulses) were described. These studies also show that brains are chaotic systems that do not merely "filter" and "process" sensory input. They actively

seek sensory stimuli as raw material from which to create perceptual patterns with awareness that replace stimulus-induced activity. This review sketches the neurodynamics of a prototypical sensory lobe of the brain, the ways in which it is controlled by the forebrain in the mechanisms of attention, the development of the complex system through bifurcations during learning, the formation of classes by generalization, their access by state transitions, and the role of chaos in constructing new attractors in cerebral cortex as the basis for consciousness.

### **Neurodynamics in a Prototypical Sensory System (the olfactory system)**

The olfactory bulb is a semi-autonomous unit that interacts with other parts of the forebrain by both transmitting information and receiving regulatory feedback. Its endogenous activity persists after it has been surgically isolated from the rest of the brain, which shows that its basic functions are self-organizing. However, its chaotic activity disappears when its parts have been surgically disconnected, showing that its chaos is a global property that is not due to the entrainment of single neurons acting as chaotic generators. The gamma rhythm (20-80 Hz) of the inhalation olfactory rhythm arises from the cyclic interaction of excitatory and inhibitory cell populations, as a consequence of delays imposed by (or measured as) the pulse-wave conversions. Essentially, the excitatory cells drive the inhibitory cells with about a 5 millisecond lag between the onset, to the peak effect. The inhibitory cells, which are partly coupled to the excitatory cells driving them, return inhibition with the same delay. Transmission between the populations is by action potentials. If the feedback system of cells is excited externally by an electrical stimulus (an impulse), whether it is given to the olfactory system or to the neocortex, the output is a damped oscillation at a frequency in the gamma range. This explains the correlation of the EEG with cell firings in the gamma range in the olfactory system and also in the neocortex.

When brain function is observed during time spans of minutes to hours, the olfactory dynamic mechanism appears to be robustly stable over a wide range of amplitudes. It can be destabilized by excessive excitation, when it jumps to an alternative stable state. This jump is called a phase transition, because it is analogous to the change from a liquid to a solid state, that is, from a relatively disorganized state to a more ordered state. In the olfactory system, the phase transition has the appearance of a change in the EEG from a chaotic, aperiodic fluctuation to a more regular nearly periodic oscillation. In state space the basal background EEG gives a pattern that looks like a bowl of spaghetti. After the transition, the pattern looks like a doughnut. An example of the orderly state is shown in Figure 1, which is a picture of a simulated EEG trace from a model of the olfactory system during an oscillatory discharge during perception of an odor.

The olfactory system can also be destabilized by neurochemical modulatory input from other parts of the brain, as with transition to the stable state of sleep, or with learning. 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.

### **Proactive Adaptive Dynamics**

Some scientists 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), proceeds through "binding" of the parallel activity of multiple features to represent objects, 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, and after an appropriate value or meaning has been attached to the fused image. 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 (Freeman 1995). The motor 'commands' that issue through the septum and amygdala are accompanied by preafferent 'corollary discharges' 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. Brain theory suggests that the cyclical process of emergent goal-seeking, preaffference, and sensory feedback constitutes the basis for what we perceive subjectively as attentiveness leading to consciousness. This inference is supported by the state of "absence", when the normal chaotic dynamics is suppressed, for example in an epileptic state. The construction of each pattern is guided by a chaotic attractor, which was formed during learning. Perceptions are triggered by stimuli, but they are shaped by connectivity patterns that were laid down during the past learning, and by neural messages from the limbic system that modulate the attractor landscapes of the sensory cortices. The images of memory are not "stored and retrieved" as in computer systems. The construction of a pattern following a stimulus is not a representation of the stimulus. It is a retrieval of the history of past experience and present significance of the stimulus for the subject receiving it, which is done by a creative construction in the limbic forge (Figure 2). The dynamics revealed in these systems may assist us to understand the mechanisms of perceptual disorders that are found in attentional deficits, hallucinations, and more generally the failure of communication among humans.

### **Learning and Brain Dynamics**

Learning in animals usually occurs when a reward or punishment accompanies a novel stimulus. If reinforcement is not given, then habituation takes place, by which the neural system decreases its sensitivity to the stimulus on repeated presentations. The decay rate of the impulse response increases, showing an increase in stabilization. This process is fully reversible. It is likely that learning is always a combination of processes for association and habituation. Input that is wanted is reinforced, and input that is unwanted is habituated. Both processes are necessary for learning. - Connection strengths change only in the excitatory net in accordance with a modified version of--the

Hebb rule. The system does not learn single events but assigns inputs into classes (Yao and Freeman, 1990), corresponding to its generalization gradient. The output of the bulb 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. 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 everywhere in the bulb. In this way the bulb transmits its own created pattern and not the imprint on its activity of the sensory input. The same modes of operation have been found in the visual, auditory, and somatosensory cortices (Barrie, Freeman and Lenhart 1996). The conclusion is that the brain can only know what has been constructed by its sensory cortices under its control and guidance. Learning therefore takes place by a structural change in the system, such that its behavior in the future is dependent on past experience.

### **A role for Chaos in Hebbian Learning**

If the inhaled air does not contain a known odorant but a novel chemical, then bursts fail to form, and the spatiotemporal patterns are disordered. Activity does not conform to any pre-existing spatial pattern. This suggests an important role for chaos in Hebbian learning. Strengthening of a Hebbian synapse requires concomitant activity in both the presynaptic and postsynaptic neurons. When this activity is organized by an already existing wing of an attractor, then the existing spatial pattern of output. If a new pattern is to be created, then the activity that enables the synapses to change must have no previous spatial pattern. A chaotic generator appears to be an optimal way that the bulb can provide novel spatial patterns of neural activity, which can then be consolidated by the learning process. Much remains to be learned about the neural dynamics of perception and cognition, and their emergence as the outcome of intentional actions created by the limbic system. These studies already show that the way to comprehend complex systems is to understand the rules by which they organize themselves, using their own endogenous chaotic activity for the creation of novel patterns.

### **Directions for future research**

Enjoyment of the full benefits from nonlinear brain dynamics will require extensive development of the basic neurosciences. There are three areas in particular need of attention. The first area is study of the interrelations between the microscopic activity of neurons, as measured by their action potentials, and the macroscopic activity of populations, as measured by their dendritic potentials. An example is provided by work on the auditory cortex of the Mongolian gerbil, for which the neuroanatomy and the behavioral and tonotopic properties of unit responses to FM (frequency modulated) tones have been well established (Scheich, 1991; Ohl and Schiech, 1996), and for which the tonotopic properties of the EEG have now been mapped (Ohl et al., 1998). If animal subjects are trained to discriminate FM tones and to generalize the modulations to different parts of the spectrum, then the basis can be laid for direct comparisons of unit activities (now called activities of "feature detectors") at the microscopic (sensory) level with EEGs at the macroscopic mean field (perceptual) level. This kind of direct comparison, which is requisite for understanding the transfer functions, cannot be made in the olfactory system, owing to lack of adequate control of the odorant inputs on successive trials.

The second area is the study of the interrelations among the primary sensory cortices (PSCs) and the limbic areas, particularly the entorhinal cortex and hippocampus (Smart et al., 1997; Kay and Freeman, 1998). Two general approaches are currently proposed for the integration of multiple sensory inputs in different modalities into Gestalts. The conventional view is that inputs to the PSCs are sent by serial synaptic transmission to a succession of cortical areas, each extracting higher order features, often with relays through the thalamus, until the highest level of analysis is reached in the frontal lobes, where the Gestalt is synthesized. The alternative view proposed here is that all the PSCs are in continuous cooperation with the limbic system, and that the formation of a Gestalt is by successive first order phase transitions involving the entire hemisphere. The evaluation of these two conceptions will be made possible by simultaneous EEG recording from the PSCs and the limbic system during performance of goal-directed actions by trained animals with implant electrode arrays.

The third study concerns the dependence of chaotic neural activity on the noise that is contributed by masses of neurons. The relationship of noise to chaos is another example of the circular causality of microscopic and macroscopic activity, because the myriad action potentials of cortical neurons are sustained by global interactions of the neurons that are manifested in the EEGs. The macroscopic state both feeds on and controls the microscopic activity (Freeman, 1996). The development of adequate brain theory will depend on advances in the mathematics of chaotic dynamics. At present most of the theory has been devoted to the description of low-dimensional, autonomous, noise free systems, such as the Lorenz, Chua and Rössler attractors, which comprise twist-flip maps. Brain chaos is noisy, nonstationary, and non-autonomous. A much better model is provided by the laser, which has been described in the context of synergetics (Haken, 1983). A further development will be required in the direction of analog devices.

Simulations of olfactory chaotic activity patterns have recently made it clear that there is a basic limitation in the use of digital computers to simulate chaotic processes. Chaos has the property of infinite sensitivity to initial conditions, so that chaotic processes are continuous in time and space. Digital computers used binary integers, which digitizes and compartmentalizes representations of continuous events. As the result, chaotic simulations degenerate into quasi-periodic and point attractors, from which they cannot recover. Although the simulations can be improved with additive noise (Freeman et al., 1997), the computational theory is weak, and the way is opened to solving the differential equations by analog simulation (Eisenberg et al., 1989), seeing that noise is essential as well as unavoidable.

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### **Figure Legends**

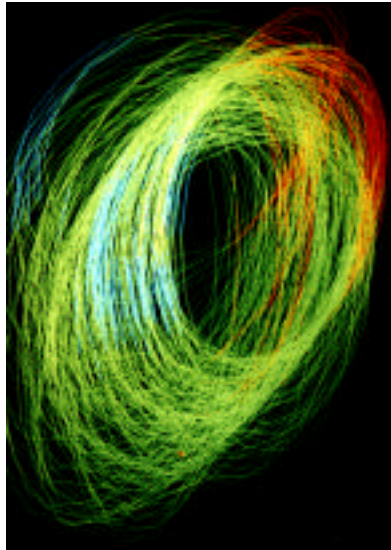


Figure 1. A computer-generated pattern simulates a burst of EEG activity in the olfactory bulb, which is triggered by the presence of an odor that an animal has learned to identify. The pattern defines a chaotic attractor, which is shown here embedded in four dimensions: the three Euclidean dimensions defining a torus (doughnut shape) and time as shown by the color of the trajectory. From Freeman, 1991.



Figure 2. The "Limbic Forge" is a surreal representation of the dynamics of the limbic system, which is centered in the hippocampus ("sea horse"), which sucks up information from the environment through its controls of the eye, ear, nose, and hand. By the dynamics in its action space in the base of the brain, it creates the patterns of understanding that inform the cerebral cortex. These informing patterns provide the windows by which we look into the world, and by which we see ourselves peering into our own windows. Haken H (1983) Synergetics: An Introduction. Berlin: Springer.