Chaotic dynamics versus representationalism. *Behavioral & Brain Sciences 13: 167-168. Freeman WJ, Skarda CA (1990)*

Walter Freeman: Authors' Response

For: Chaotic dynamics versus representationalism

A Putative Role For Transient Local Coherence In Cognitive Function

BEHAVIORAL AND BRAIN SCIENCES (1990) 13.1; Continuing Commentary

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For many years the work reported from the laboratory of Walter Freeman has been focused on identifying the neural mechanism responsible for learning and recognition of odors. In their recent *BBS* target article, Skarda and Freeman (1987), (S & F) use the language of neurophysiology, statistics, and nonlinear dynamical systems theory to describe such a mechanism. For this commentator their article is particularly noteworthy for the following reasons:

(1) The description of the proposed mechanism is firmly based on classical neurophysiological measurements and current understanding of membrane properties, single cell dynamics, and neuron-neuron interactions. Included in these measurements is an important test-of-hypothesis experiment in which the spatial EEG pattern recorded from the olfactory bull) (OB) surface was shown to be an excellent predictor of the animal's behavior (Freeman & Viana Di Prisco 1986).

(2) It is coherent (cooperitive) functioning of the entire mitral and granule cell population of the OB which apparently allows the recognition of the pattern of sensory input corresponding to a learned odor. S & F describe

how coherence is induced in this large cell population (108 - 109 neurons) and how patterns of enhanced connectivity within the mitral cell population develop and subsequently give rise to distinct and recognizable patterns of physiological activity.

(3) The OB and ipsilateral prepyriform cortex arc described as an integrated dynamical system whose behaviors are organized along a single dimension, namely, the excitability of the mitral cell population of the OB, As excitability increases, the OB EEG displays quiescence (flat line), low-level chaos (random appearance), limit cycle/chaotic bursts (pure/frequency-modulated sine waves), and finally high-level chaos (epileptiform) activity. Distinct and recognizable limit cycle states occur in correspondence with behavior indicating recognition of different learned odors.

The findings and interpretations reported by S & F provide a powerful and potentially important general perspective on neural tissue function. Of key importance in this regard is determining whether similar mechanisms are operational in brain processes mediating functions other than odor recognition. Results of such studies have been reported for the visual system of *(he* monkey (Freeman & van Diik, 1987; Cray & Singer, submitted) and the visual system of man (Krieger & Dillbeck 1987).

The findings, interpretation, methods, and language of dynamical systems reported by S & F provide a different and potentially important perspective on behaviorally relevant neural function. This perspective warrants additional study in other laboratories.

Authors' Response

Chaotic dynamics versus representationalism

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We thank Krieger for his concise summary of the main points of our target article and for citing pertinent references to other and more recent work in this area (including his own excellent studies on behavioral correlates of high frequency EEG gamma activity in humans) that provide further evidence that brains code high-level cognitive information in the macroscopic active states of masses of nerve cells. His commentary gives us an opportunity to update tile views we presented in our target article (Skarda & Freeman 1987) in two respects.

First, three years ago we envisioned that the basal chaotic state that exists in the olfactory bulb during exhalation was destabilized during inhalation, and that after a transition phase (modeled as a Hopf bifurcation) odorant input then facilitated convergence to a learned activity pattern modeled as a limit cycle attractor. On the basis of further modeling with nonlinear differential equations and a review of our data reflecting experimentally induced sustained oscillatory states of the olfactory system, we now believe that the EEG "burst" that carries the perceptual information from the bulb to the prepyriform cortex is not the manifestation of a limit cycle but reflects instead another chaotic attractor. We do not offer this as a firm conclusion, but rather as a more plausible hypothesis than the one originally presented. It is likely that there will remain substantial uncertainty for some years, possibly decades, about the differences between a limit cycle trajectory that aborts prior to convergence to a periodic attractor, a limit cycle attractor under perturbation by noise, and a narrow spectral band chaotic attractor in which the unpredictability appears in variation of phase or in frequency narrowly about a mean. We think that the problems of the experimental distinctions are not as important, however, as the theoretical realization that bifurcations in neural masses on sensory perception and pattern recognition may be from one chaotic state to further chaotic states of different kinds, rather than from equilibrium or chaos to limit cycle and vice versa. Mathematicians will recognize that these kinds of bifurcation in distributed systems pose major problems for understanding, and that finding theoretical descriptions will require developing nonlinear dynamics to levels far beyond those presently attained.

Another change in our understanding concerns our data from the olfactory bulb, which indicate that neural activity emerges from a low-level chaotic state to a more ordered form of chaos manifested in the burst reverting once again to the same basal state. More recent modeling in our laboratory (Freeman et a]. 1988). indicates that convergence to a burst pattern is independent of the initial conditions at the onset of the bifurcation. This suggests that the system is not obliged to reset to a basal state before being challenged by a new input to converge to a learned information-bearing attractor state. We now see in the recordings we and others have made from the visual cortex (Eckhorn et al. 1988; Freeman & van Dijk 1987; Gray & Singer, 1989) an alternative form of "frame of reference" that contrasts with the olfactory time series. Instead of being separated by the exhalatory basal state, the "bursts" in visual cortical EEG may run together into an unseparated set of frames. This suggests that, to the extent that olfactory and visual cortices work by the same basic algorithms of neural mass action, the visual neocortex may have a longer frame duration or a faster frame rate. We have no experimental means as yet for making this determination, but the implications are fascinating.

Our view is that neural dynamics in perceptual processing is most accurately modeled by invoking a complex cluster or hierarchy of chaotic states. Because chaotic dynamic activity is extremely complex, taking seriously its role in the brain frees the view that what the brain does when we perceive something is to ingest, store, and recall an internalized correlate of the input. In the light of our recent findings, this representationalist view of brain function appears outdated because it involves concepts that predate the discovery of chaotic dynamics and it misleads by creating spurious problems.

Yet representationalism is hard to abandon even when we become aware of its problems. In retrospect, perhaps even the hypothesis of our target article that patterned activity of a limit cycle variety plays a role in perceptual processing in the bulb was still partially wedded to representationalism. Chaotic activity had a role to play in that model: We hypothesized that it gives the system the speed, flexibility, adaptiveness, and open-endedness it needs to learn. By implication, however, we conceived of the signal episodes quite differently. They did not possess the same flexibility and were stereotypic, repetitive, simple patterns of activity. If our current data are correct, we will have to relinquish even this remnant of the old view of brain function. Brain dynamics are shot through with flexibility and adaptiveness, complexity and speed. On the basis of our current data we hypothesize that the brain no more needs to return to a basal state to prepare to receive a new odorant than it requires a periodic oscillatory pattern of activity or correlation with a particular input pattern. The down-time between perceptual frames is thereby minimized to the brief duration of a switching transient and the perceptual process may move with the seeming smoothness of a video.

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