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Continuing Commentary

On Ebbesson, S. O. E. (1984) Evolution and ontogeny of neural circuits. BBS 7:321–66. 547

On Hobson, J. A., Lydic, R. & Baghdoyan, H. A. (1986) Evolving concepts of sleep cycle generation: From brain centers to neuronal populations. BBS 9:371–448. 549

On Foreman, N. & Stevens, R. (1987) Relationships between the superior colliculus and hippocampus: Neural and behavioral considerations. BBS 10:101–51. 552

On Skarda, C. A. & Freeman, W. J. (1987) How brains make chaos in order to make sense of the world. BBS 10:161–95. 557

How might brains work?

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Since the publication of "Mass Action" (1975) Walter Freeman's work has interested anyone concerned with the question in my title, but especially those who think that there may be a biophysical explanation for the human experience of consciousness, from which all human intellectual and cultural behavior begins. When we start to introspect, daydream, rationalize/verbalize, induce and deduce – from this only possible origin of our immediate consciousness (as Einstein is supposed to have said he did) – we are struck by the impression that this immediate experience bears little resemblance to the rule-based symbolic operations of traditional von Neumann machines, as von Neumann himself saw (Freeman, in press). But when we want to win a game of chess, pay our bills quickly, or solve one of those old-fashioned literary crossword puzzles, we feel we are behaving more like a binary, digital program (or at least we wish we could). When called upon to attempt logical and mathematical inductions and deductions, we like to think we are performing as connectionist machines, multiparallel but preferably fixed-point. And when hoping to talk or write creatively, we invoke the Muses of Determinstic Chaos and seek their guidance across saddles and into basins of passing attraction; unhappily, most of us get stuck in local minima and become limit cycles or bores.

Isn't it just possible, even probable, that our "Darwin Machines" have survived so far precisely because they have conserved all of the above modes of operation? That is the strong impression I get from reading the invited commentaries on Skarda & Freeman (S&F). But then I have no subsidy-seeking axe to grind! Grey Walter of the Burden and DeMott have sure priority in spatiotemporal displays, but all one could really say was "Wow!" In the 1960s John Paul Nafe tried to show hardline sensory specificists (I hope Ainsley Iggo won't be offended) the common sense of spatiotemporal pattern theory in the periphery as well as in the CNS, and not just in olfactory-gustatory systems. Nothing is wholly new in the solar system, at least, but occasionally a few people get a bit further; this is the merit of Freeman's laboratory. I am not enamored of his Mexican "hats" and would much rather gaze at Murphy's "eyeballs" (Davis 1960); I don't believe that all of the brain, all of the time, works like his olfactory bulb and piriform cortex, but I am sure that some of it does, some of the time; and some of that biophysical activity is certainly the stuff of our conscious experience. Since olfactory behavior is so important to most mammals other than primates, it would not be surprising if we had retained a large part of that peculiar functioning and adapted it to other uses.

I'm surprised that nobody mentioned, among mathematical theorists who may be catching up with neuroscientists like Freeman, the group at Las Cruces, N.Mex. (Cohen & Julian 1987), whose initial conditions are introspection rather than robotics, but who say that it is now up to the materials physicists to devise weakly nonlinear, quasi-crystalline, dispersive media similar to neural/neuroglial tissue before their quasi- and super-holographic models can be tested in computational mode.

Another thing that continues to surprise me about this long-standing debate between computationists of several schools is the tacit acceptance by all of them of an axiomatic dimension of both physical and biological "time." The early psychophysicists, who were founding fathers of experimental biopsychology, were much concerned with this oddball dimension and its biologically apparent irreversibility and unidirectionality. Every discussion of and simulation with computational models must use this dimension; but where, when, and how in the CNS does it come from? It can't all come from a single "alpha," "beta," or "gamma" clock, but it might come from mixtures of many frequencies (Stowell 1987).

Authors' Response

Research options and the "creativity" of chaos

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We welcome **Stowell**'s commentary. He is right to argue that brains may be organized at the functional level in many different ways to produce a wide range of cognitive and noncognitive behaviors. Nothing in the target article (Skarda & Freeman 1987) precludes this. Our main point was that olfactory functioning is best described as a distributed, self-organized process whose functional architecture resembles current connectionist systems (given certain important modifications), and hence that the digital computer model is not adequate to account for *all* cognitive behaviors as had been maintained. We are convinced that a too narrowly conceived research program is a roadblock, be it one based on digital or connectionist systems. Proponents of connectionism should take care lest they fall into the very same dogmatic trap that led the digital paradigm to its current discredit. Diversity is the key, not just for biological evolution but also for the development of science.

However, we think it is misguided to imagine, as Stowell does, that current computer technology or introspective impressions are the best or only guides to understanding how brains might work. Historically at least, introspection has revealed precious little concerning the principles of neural organization responsible for cognitive behavior, and it is conceivable that connectionist research may eventually go the way of watches and the telephone exchange as metaphors for brain function, or (as seems more likely given the present state of knowledge) that connectionist models may be transformed by further neuroscientific research into actual simulations of brain dynamics as we understand it. If what we want to know is how brains might work, then we believe that the best bet is to study brain dynamics.

One final point: Chaos has become fashionable, and as such there is a danger that the term will become meaningless. There are hints in Stowell's commentary that it already has suffered this fate. Our point was not, as Stowell implied, that chaos is necessary for "creative" cognitive activities (e.g., writing or story telling), whereas more mundane activities (e.g., adding) are based on (by implication) less creative, digital, binary architecture. Our claim is that chaotic activity in the olfactory bulb is the essential precursor to the emergence of the ordered states responsible for odor recognition. This process is self-organized: The brain organizes its own space-time patterns and thus its own structure; they are not imposed upon it by incoming stimuli. In this sense, brain dynamics are creative, as opposed to reactive. However, this does not imply that the cognitive processes that result are "creative" in Stowell's sense. On a scale from 1 to 10 for creativity in Stowell's sense, preconscious odor recognition in rabbits must rate pretty low. We have not argued that deterministic chaos plays a role solely for the sake of the higher cognitive states we ordinarily refer to as creative; on the contrary, our evidence indicates that very primitive cognitive states essentially involve chaotic dynamics.

Too soon for time and consciousness

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In raising for consideration the concepts of time and consciousness, **Stowell** pushes the discussion logically to a new level that is well beyond the scope in our presentation in Skarda & Freeman (1987). We limited ourselves to theory that we could support or undermine with our experimental data. An act of perception exists at a moment and therefore outside of time. True, it has its antecedents and its consequents, but they are implicit; the experimental analysis is carried out on data off-line and with little regard for sequences of events. Our collections of acts of perception from our rabbits, having the form of sniffs of odorants and bursts of EEG waves, were like black and white balls in an urn.

What Stowell would like us to consider is the assembling of percepts into a stream, which is the stream of consciousness. A problem is that the flow of olfactory percepts can only make sense in its relations to the flow of respiratory commands that emanate from the limbic system, and the flows of proprioceptive and other exteroceptive percepts. These flows combine continually in the entorhinal cortex and synthesize over recent time in the hippocampus. As Harry Klopf (1982) suggests, consciousness appears in this interplay of afference and reafference. As Stowell suggests, the biophysical route to understanding the neural mechanisms and functional role of consciousness is in principle open to us.

But the experimental basis for the analysis is far from adequate at present. We have no idea what physiological form is taken by the several kinds of bursts in the entorhinal cortex, or how they are combined, or how strings of percepts are assembled to form concepts, or how concepts are fed back to primary sensory cortices to control sensory input and the formation of new percepts. No one knows what a reafferent message looks like. Even if we had a model or two to guide our thinking, we do not yet have the techniques to gain access to the spatial patterns of the entorhinal EEG. This cortex faces onto the floor of the skull in the deepest and best-protected recess of the head. No serious progress can be expected until the surgical problem of gaining access is solved. In our opinion, the greatest single obstacle to answering Stowell's question is the petrous portion of the sphenoid bone of the skull, the hardest bone in the entire body.

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