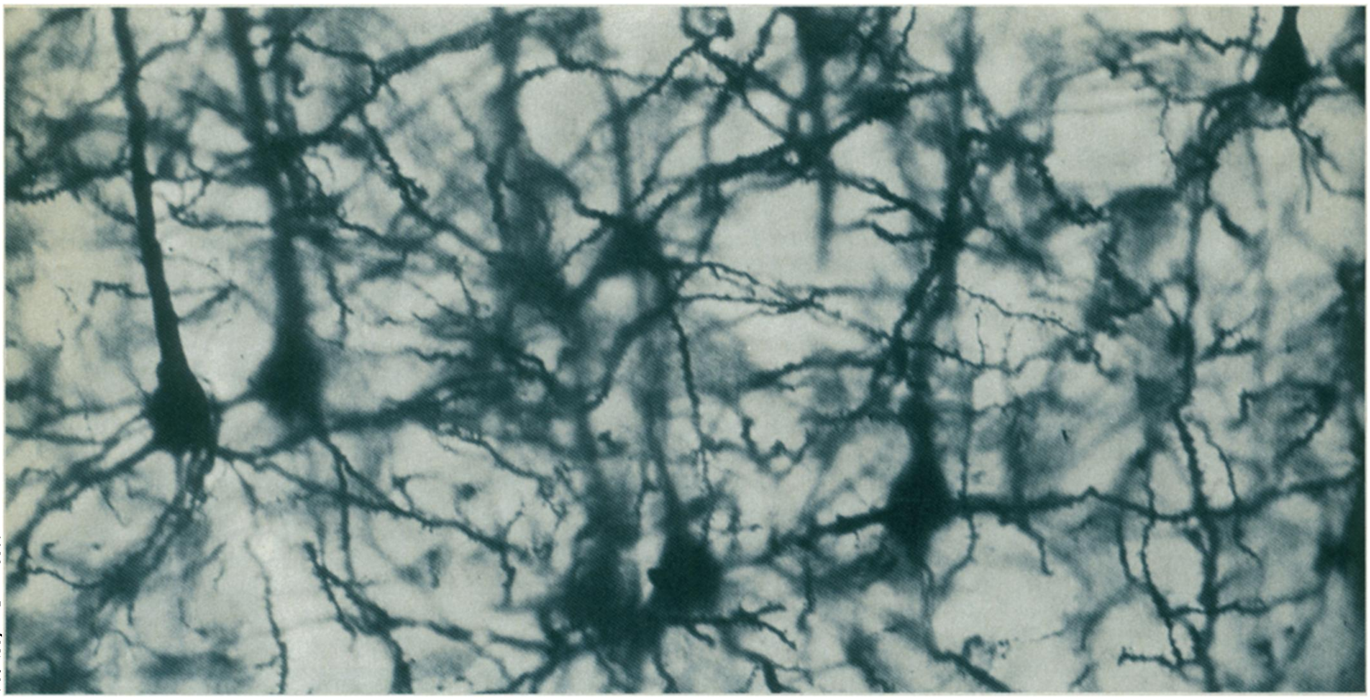
Chaotic Connections

Do learning and memory spring from chaos generated by brain cells?

Courtesy: FIDIA Research Labs.



By BRUCE BOWER

Pity the poor neuron. The brain contains tens of billions of these nerve cells, but each one fires off chemical messages to its neighbors at the rate of less than once per millisecond, a plodding tempo considering the welter of information flooding the senses. What's more, individual neurons are unreliable. Thousands of them tire out and die every day.

But fortunately neurons tend to pool their resources, by the millions, and bounce waves of electricity off one another in preparation for greeting incoming sensations. What's more, according to philosopher Christine A. Skarda of the Polytechnical School in Paris, France, and neurophysiologist Walter J. Freeman of the University of California at Berkeley, the cooperative crowds of cells generate the chaos necessary for the brain to make sense of the world.

Skarda and Freeman do not use chaos in the broad sense of the word, as a tag for helter-skelter activity. They are borrowing from the young science of chaos, in which computer models based on mathematical calculations reveal patterns in seemingly random physical events, from flags flapping in the wind to the flow of water drops from a faucet. In a living organism, says Freeman, the difference between biological activity reflecting random "noise" and that reflecting chaos is like the difference between the noise of a crowd at a ball game and the noise of a family quarrel.

The scientists propose that a low hum of chaotic activity in the brain generates a flexible "I don't know" energy state, from which massive numbers of neurons can be prodded instantaneously to work together and respond to new as well as previously encountered sensory stimuli without getting hopelessly confused.

The road to this theory of chaotic activity in the brain began more than a decade ago. Freeman and a number of colleagues began to probe the olfactory system of mammals, because it is the simplest and best understood sensory system. They theorized that when an animal inhales an odor it has been conditioned to respond to in some way, specific information on the olfactory bulb of the brain – the first stop for the stimulus once it has passed through receptor cells in the nose – mediates a correct response. Furthermore, the scientists suggested that the information is coded in distinct electrical waveforms of neural activity that can be measured indirectly by electroencephalographic (EEG) potentials recorded from the surface of the olfactory bulb.

In the last few years, some experimental support for the theory has emerged. First, the researchers conditioned five thirsty rabbits to lick in response to an odor followed after 2 seconds by access to water. The rabbits were then trained only to sniff in response to another odor. Each animal had 64 electrodes implanted on its olfactory bulb so that EEG traces could be measured during conditioning.

Correct responses to the two odors corresponded to specific electrical waveform patterns common to all 64 channels and, suggest the investigators, to the entire olfactory bulb. The electrodes did not cover the whole bulb, but encompassed an area consisting of hundreds of millions of neurons. Freeman and his colleagues hold that every neuron in the bulb participated in the bursts of electrical activity and each must have played a role in identifying smells.

After observing the smell-specific EEG activity, the researchers translated the average resting or "spontaneous" EEG of the rabbits into mathematical equations.

They developed a computer model for the olfactory system, from nasal receptors to the olfactory bulb to the prepyriform cortex, another brain area involved in the sorting and storage of smells. The model also accounted for delays and gains in smell transmission caused by the feedback of various types of neurons in the system.

This model yielded sustained activity that was statistically no different from the background EEG of resting rabbits. Mathematical analysis of the ebb and flow of the naturally occurring electrical spurts, note the investigators, indicates that they reflect chaos rather than random noise.

"Chaos [in the brain] is controlled noise with precisely defined properties," says Freeman. "It can be turned on and off virtually instantaneously, as with a switch."

In the case of the rabbit's olfactory bulb, he says chaotic activity switches on and off during the course of respiration. During late inhalation and early exhalation of a conditioned smell, a surge of receptor input sensitizes probably only a select subset of olfactory bulb neurons that then induces the appropriate electrical waveform burst out of the remaining bulb neurons. As a result, there is an abrupt shift from a low-energy chaotic state to a high-energy state. Freeman proposes that with each inhalation, every electrical waveform pattern linked to a particular odor is available to an animal. No search through a memory store is required; memory for an odor consists of a set of strengthened connections in a key subset of waveform-triggering bulb neurons.

An unfamiliar smell, on the other hand, results in a chaotic, relatively low-frequency burst from the bulb that, with repeated reinforcement, can lead to a signature electrical waveform pattern.

This is not the only recent model for learning and remembering smells (SN: 1/9/88, p.29). In addition, acknowledges Freeman, there are weak points to the chaotic version of odor sensation. The mathematics of a "chaotic generator," particularly in living organisms, are not highly developed. Furthermore, the theory does not address complex types of learning that require sustained attention and motivation.

But it does fit into and extend a branch of psychological research known as connectionism or parallel distributed processing, say Skarda and Freeman in the June Behavioral and Brain Sciences. Rather than breaking down certain types of thought processes, such as those involved in memory, into rules, operations and tasks, connectionists use computer models to study how a brain might generate rules or recognize sensations.

Learning in a connectionist computer is based on mathematical calculations that adjust the strength of connections linking up "neuron-like" processing units. The connections are thought to be comparable to synapses, or junctions between neurons that transmit chemical messages across cells. A given stimulus fed into the computer activates the whole network, including various feedback mechanisms that alter the strength of designated connections. If the connections have been properly "weighted," the correct response is produced.

Both the chaos model and connectionist systems rely on the distributed activity of units or neurons in cooperative networks that produce behavior without relying on rules or symbols, says Freeman.

But in some ways, he notes, the complexity of the brain's neural system eludes connectionist setups. For instance, the dense feedback connections of olfactory bulb neurons and the neuron assemblies that take charge of odor memories are poorly represented in computer simulations. The ability of the chaotic background state in the olfactory bulb to respond to new as well as to familiar input without an exhaustive memory search is also lacking, he adds.

The hallmark of some connectionist models is the ability to run part of a pattern through the appropriately weighted units in the "neural network" and come up with the whole pattern. But pattern completion loses its meaning in the olfactory bulb, says Freeman. Chaos is the rule, and the patterned activity to which the neural system rallies following an encounter with a smell is never twice the same.

The design, construction and maintenance of the nervous system appears to be sloppier than a precisely weighted connectionist model, he says, "but [chaos] is a quality that makes the difference in survival between a creature with a brain in the real world and a robot that cannot function outside a controlled environment."

The survival of Skarda and Freeman's theory of chaos in the brain is challenged, however, by a recently developed computer system that improves on pattern recognition and completion. Called adaptive resonance theory (ART) architectures (SN: 7/4/87, p.14), this type of neural network creates and organizes categories for objects and responds instantly to new experiences, all without reliance on a background chaotic state.

The ART system, devised by Gail A. Carpenter of Northeastern University in Boston and Stephen Grossberg of Boston University, is not a model of the olfactory bulb. It codes preprocessed images on a series of levels. An image enters the first level and is sent on to be matched with an appropriate category stored in upper levels, which at the same time are sending down signals to ensure that a good match exists. If no adequate match is found, the system creates a code for a new category.

The latest incarnation of ART architecture, ART 2, rapidly makes subtle distinctions between similar images and directly calls up a category when it sees a familiar object rather than conducting a lengthy search process.

"We've mathematically shown that chaos is not necessary to achieve the type of competence described by Skarda and Freeman," says Grossberg.

He also notes that it is unclear whether chaotic properties have anything to do with overall brain organization. It is more likely, he says, that active hypothesis testing, something akin to the matching and search procedures of ART 2, reorganizes the brain's energy landscape.

The olfactory system, responds Freeman, cannot carry out the precise comparisons and retrievals of ART architecture. For example, a rabbit conditioned to respond to a series of four odors will display a new olfactory bulb electrical waveform pattern for each smell. But if it is again conditioned to the first odor, the waveform assumes a new shape rather than reverting to its initial pattern. There is no sure way of knowing how much of the original information is retained by the rabbit, says Freeman, but changes in experience and in the learning situation probably alter the associated brain activity.

According to René Thom of the Institute of Advanced Scientific Study in Bures-sur-Yvette, France, the EEG activity of the conditioned rabbits might also be altered by a different conditioning stimulus – say, by subsequent electric shocks rather than access to water. The unknown effects of the experimental procedure on olfactory bulb waveform patterns point to a gap in the findings, writes Thom in a response accompanying the Skarda and Freeman article.

In addition, he notes, if a specific subset of bulb neurons triggers each odor memory, then there must be an infinite number of such neural assemblies for all possible odors, "something difficult to accept."

Skarda and Freeman do not claim that the olfactory bulb has an infinite storage capacity for odors, but they have not yet explored how new odor-specific groups of bulb neurons are integrated into preexisting ones or what happens to the old ones.

"Thom is too generous in characterizing our . . . data as having gaps," says Freeman. "At best, they constitute a small clearing in a large forest." It remains to be seen, however, if the two scientists are barking up the right trees. □