The Creation of Learning and Memory

BY JAMES OLDS

Understanding Education

The human brain is above all an educatable machine. For this naturally selected computer we have a set of cultural programs that have been perfected over the centuries by a kind of dog-eat-dog competition between ideas and societies. Sad to say, we still do not understand either the basic machine or the programs, though we are continually called upon to make patches to overcome obvious deficiencies.

Eugenicists offer to solve the range of our problems by supplying us with a new and better computer—the genetically planned human—but there are reasons why this answer is not sufficient. One is the danger of losing from the pool of genes some that might be needed later for reasons not known to us now. Another is that people are irrationally attached to their genes.

The alternative is teaching, education—programming, if you like. In the past we have been lucky; each national culture has pressed forward, improving its educational tools by repeatedly choosing the winner in a battle of ideas, and eliminating the ones that did not do well. Our sense of how to educate came not from understanding but from success.

But to solve new problems rationally we want understanding; it is a natural urge that we cannot stifle. One course is to seek a sensible theory of brain function, which should illuminate to some degree the basic quandaries of education. What are these quandaries? The first has to do with punishment. Does punishment guide behavior in organized pathways; or does it make neuroses and suppress creativity? We really do not know much about what kind of learning profits by punishment and what kind is better off without it. Human "imprinting" is another quandary. The church, for example, used to worry a good deal about the rote-fare a child was exposed to prior to the age of reason. Now, those who control the radio and TV assure us that this is no problem. We really do not know what the steps are in building the early "systems programs" for the human being. Mothering the very young at all hours is a third quandary. It is offered by some as a prescription for the child's eventual mental health. But others answer that a mother who divides her time sensibly among her work, her grown-up pleasures, and her children is better off from the point of view of her own mental health—and thus better for her children. We really know very little about the influences of a mother's contacts, her gestures, her early words, and other such things.

When we get children into school, there are more questions. How should we teach? How much reading? How much feedback? How much repetition? How can we keep the child interested? How can we force him to do what he needs to do to live a full and happy life? What kind of grading system? What kind of rewards and penalties? How much praise and blame? How much homework? How often, if ever, should a child "fail"?
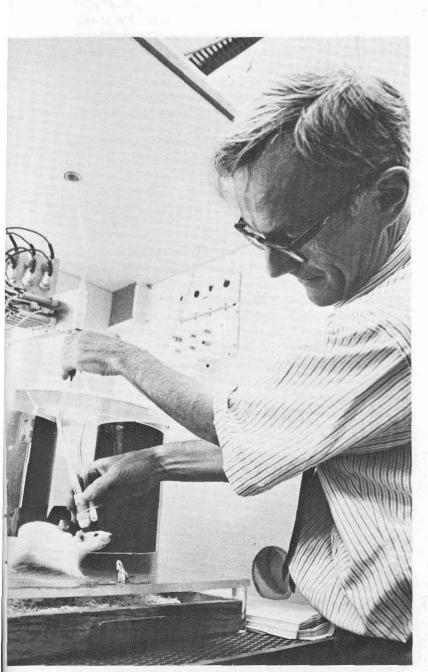
I could make another list of questions for education in employer-employee relations, or in adult interaction (mutual education). In the end we are all programmers of people.

Underlying Problems

A web of basic scientific questions lies just under the surface of these practical problems. If we could frame the questions properly, we would have taken an organizing step toward a good theory. We cannot. But we do know something about them.

In dealing with these questions we are interested in the creation of memories—different kinds for different purposes. We are interested in making some memories durable (values, perhaps) and some transient (anxiety, for example). We are interested in making some memories readily accessible so that they are available for repeated use in the course of the day. We are interested in the interaction of memories—so that they do not upset one another; and so that some (like systems programs) serve an organizing function in relation to others. And, finally, we recognize the overriding importance of the problems of interest, attention, sanction, motive.

Our studies are aimed at the problems of memory, learning, and motivation of learning at the most basic level. We are trying to find what the basic organization of the brain has to tell us. Our primary aim is not to find answers to the practical questions but to find organizing

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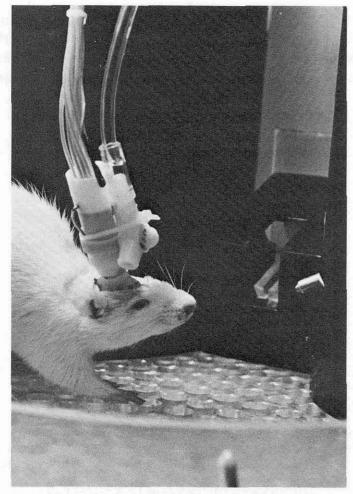ideas that will inject wisdom into our search for those answers.

Our interest is in the human brain, but we work with the rat because this animal has a miniaturized copy of the human brain. Many of the major parts are the same, both as to internal wiring and to relations between them.

What We Do with Rats

In our experiments, we implant the brains of anesthetized rats with many probes in each brain. When the rats wake up, they are behaviorally active, alert, and ready to play experimenters' games. They are "plugged in," and an "umbilical cord" from the probes carries messages to the computer during the experiments. Rats have a long genetic tradition of doing well even under bizarre conditions, so they quickly come to behave as if they are used to and happy with the cable system.

Our probe-and-cable system is used to record electrically the signals of the neurons in the brains of the rats. Neurons, like crickets, emit repetitive outbursts when they are active. In crickets it is an outburst of clicks; in nerve cells it is an outburst of "electrical spikes." These are picked up by our probes, amplified for display on an oscilloscope, and counted by a computer. The spikes are ongoing, but a stimulus that affects the neuron (such as an auditory signal from a loudspeaker) causes an acceleration or a deceleration, a change in the number of spikes per second. Our probes touch several neurons, but we can distinguish the spikes from each by automatic electrical sorting techniques. We could count the activity of just one neuron; but we are not usually this selective. Usually we count spikes from a small group (six or seven neurons). But this allows us to track the path of an incoming signal in the brain.

Our method is to apply an auditory signal with a sharp onset and to trace the resulting neuronal activity, in successive time frames, through the various stations of the brain. We thus establish a message map of the course of the signal. We first do a control experiment and make a message map for a habituated signal that has become meaningless to the animal. Then we add meaning to the signal by a "Pavlovian conditioning experiment." This is done by presenting food one second after the signal; because the animal is hungry, the auditory signal begins to elicit behavior directed to the food. During this period when meaning is added to the auditory signal, we make a series of successive message maps.

James Olds, Bing Professor of Behavioral Biology, makes studies with rats to learn more about the problems of memory, learning, and motivation at the most basic level.

A two-way probe-and-cable system uses sound signals to stimulate neurons in the brain of this rat and record his responses in successive stages of a learning situation. The resulting series of message maps trace the pathway for the formation of a memory. In this case the rat is learning to associate the presentation of food with a sound. There are nine white cables on the left which carry electrical spikes from the different brain probes. The transparent plastic tube on the right carries the auditory signal to the animal. To the right of the animal are the food magazine and the water spout.

By overlaying these successive maps, it is possible to trace out a family of changes that succeed one another during the course of training. And for each of these changes it is possible to gain some indication of where the message branched from its old pathway into a new one as a consequence of the training procedure.

Auditory Tuning
Training caused the signal to branch off into new paths at almost every station of the auditory pathway. It also caused preexisting responses in the auditory centers to be modified, usually to be amplified or enhanced. There was also a substantial change in the background firing rate—the so-called spontaneous discharge rate of neurons in some of the auditory areas.

The amplification of the auditory responses was observed even at the very first brain station of the auditory path; it may also have involved the nerve that joins the ear to the brain. Here, after training, there was often a 30 percent increase in the spike rate caused by the auditory signal. Similar changes occurred at the other stations of the auditory pathway; in the higher centers the changes were proportionally even larger, often increasing by several hundred percent.

Were the response changes in the higher auditory centers caused by the changes in the lower centers—or vice versa? Two features made it difficult to accept the view that the changes in the higher centers were directly caused by those in the lower ones. First, the changes in the higher centers were much larger in proportion to the total response. Second, the changes in different centers often occurred at different stages of training. In some experiments, changes in the lower centers were completed in the first 60 trials of the training, while changes in the middle stations continued into the second and even third sets of 60 trials.

The timing of the responses also made it difficult to accept the view that changes in the lower centers were caused by those in the higher ones. The changed responses in the first auditory station appeared about one or two milliseconds after the tone reached the animal. Thus, there could not have been time for the auditory message to go first up to the cortex to be recognized and from there come back to cause the response in the lower center to be increased. In fact, the message would not even have had time to go to the second auditory station. Therefore, it appeared that the auditory system had to be ready for these signals before they reached the ear. The ear, or at least the first auditory station, was in some way pre-tuned to accept them.

However, a second kind of influence from the upper stations is still possible—a readiness of the lower station for the specific stimulus, maintained by some active process in the cortex (or in the middle stations). Such a process

would be developed by the training procedure, and would always be "on" awaiting the anticipated stimulus. If such a process existed, it would match what psychologists call an active or dynamic memory trace, or a psychological set.

Dynamic Memory Traces in the Cortex

The suggestion that a dynamic process in the cortex might prepare the auditory pathways led to the question of how such an influence might work and how it could be experimentally identified. A likely mechanism is well known. It is a 3-neuron dynamic switch in which the activity of a control neuron can cut off the flow of information between two other neurons. If control neurons in the cortex brought such "pre-synaptic" inhibition to bear on the lower auditory centers, then a slowing of the background firing rate in the cortex might be one way of preparing the lower centers for a signal. If so, such slowing might be observed during Pavlovian conditioning.

Dr. John Disterhoft, research fellow in biology, looked for changes of this kind. In most of the lower centers, training caused brief and insignificant changes in the background firing rates and left them well within the control range. But in the cortex there was a stable, sustained change in the ongoing discharge pattern, consisting of a 25 percent decline in the average "spontaneous" spike rate of auditory cortex neurons. Both the sustained nature of the change and its downward direction fit the view that these could be control neurons whose firing screened out the auditory signals before training. So one kind of "dynamic memory trace" could be a slowing of control neurons in the cortex resulting in amplification of responses in lower centers.

Structural Traces in the Cortex

Were these dynamic traces the only memories in the cortex? This seemed unlikely. We therefore sought evidence for other longer-lasting changes of connecting structures. Other investigators had suggested that mushroom-like contact organs (called "spines") which link neurons might be caused to grow by training procedures. If cortex neurons become more strongly coupled to input signals by the growth of spines during training, they should become more responsive to auditory stimuli. This might form the basis for a test, but the difficulty was that response changes observed in the cortex might also be caused by 3-neuron switches, like those in the lower centers. How could the two kinds of process be separated? The most fruitful idea so far has been to assume that in the case of lasting structural changes a growth process might continue for some time after training stopped. The underlying assumption is that training starts the growth of the spines, but that they continue to grow after training has stopped. To test this idea it was decided to start with an experiment in which behavior not only improved during training, but continued to improve during an extended time-out period. Disterhoft found that if he first trained animals to respond positively

to one auditory signal called the CS+, and to ignore a second auditory signal called CS−, and then reversed the significance of these two, the behavior followed an appropriate course.

After the switch, *behavior* improved in response to the new CS+, and deteriorated in response to the old one. By the end of an eight-hour training series the response to the two signals was at a middle level and about equal. If an eight-hour time-out period was then interpolated, the behavioral response to the *new* CS+ was greatly augmented, and the response to the *old* one had disappeared almost completely.

What changes occurred in the cortex during the time-out interval? The firing-rate response of neurons to the new CS+ that had been initiated by training was substantially augmented by the time-out period, just as was the
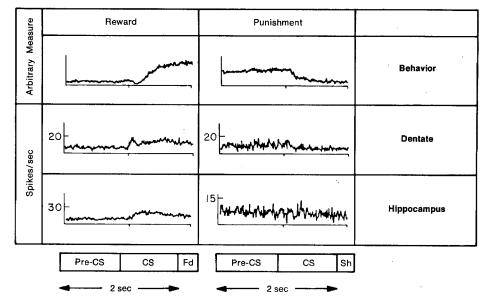
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behavioral response. However, the firing-rate response to the old CS+, which had been to some degree diminished during training, surprisingly sprang partly back to life during the time-out.

This was not exactly what we expected because during the time-out the *behavior* had improved to the new CS+ and died out to the old one. But in this period cortex firing-rate activity increased to both the new CS+ and to the old one. Thus, while the cortex changes could account for the behavioral improvement in response to the CS+ during the time-out, it could not account for the equally adaptive behavior loss in response to the CS−

In the same experiment, however, it was possible to observe changes elsewhere that could account for this behavior loss. During the time-out period a reduction in response to the CS− (without any changed response to the CS+) occurred in the neurons of the hippocampus, and in neurons in special "middle" regions of the brain which are thought to be involved in controlling attention. The experiment as a whole therefore suggested that during time-out some structural consolidation of a newly acquired positive response might have occurred in the cortex, and some similar consolidation of "extinction" or suppression might have occurred in the hippocampus or in other regions.

In any event, when changes such as these become improved (rather than disappearing) with the passage of time, the hypothesis that they are caused by some temporary *dynamic* memory process (that could die out) becomes less likely, and the possibility that the growth of a *structure* is involved becomes the more likely.

	Reward	Punishment	
Arbitrary Measure	*(behavior curve: increase)*	*(behavior curve: decrease)*	Behavior
Spikes/sec	20 *(dentate curve)*	20 *(dentate curve)*	Dentate
	30 *(hippocampus curve)*	15 *(hippocampus curve)*	Hippocampus

Pre-CS	CS	Fd		Pre-CS	CS	Sh

◄──── 2 sec ────►   ◄──── 2 sec ────►

Average rates before and during a conditioned stimulus (CS) are represented on these curves. They show that the behavior of the animals and the activity of the dentate (motive) units increased in anticipation of food reward (Fd) and decreased in anticipation of a punishing shock (Sh). The activity of the hippocampus units increased in anticipation of food but was not changed at all before the shock. The absence of any change in the hippocampus when the dentate was inhibited suggests that increased dentate activity is necessary before learning occurs in the hippocampus (which is supposed to be one kind of memory system).

Reinforcement and Learning in the Hippocampus

Reward and punishment enter the problem of learning in many ways. For higher learning, the role of reward is at least twofold. First, reward or some alerting event is required to "turn on the learning machine." Second, reward enters again to determine what behaviors will be repeated and what ideas will be rehearsed.

The hippocampus is a complicated structure rolled up inside the cortex on each side of the head. The elegant arrangement of its neurons makes it easy and interesting for neuroanatomists to study. The loss of the hippocampus in humans is known to cause a specific loss of one kind of recent memory (for daily lists and events). The hippocampus is connected so as to tie together the processed information from the association cortex with the attentional and motivational centers of the lower brain. This has led to the supposition that it may be involved in critical interactions between motivation and learning.

Experiments in our laboratory by Dr. Menahem Segal, which tracked a conditioned stimulus through the hippocampus, seem to fit this view. One particular family of neurons in the hippocampal system seems to be involved mainly in turning on the hippocampus as a learning machine during training. Then, the order of firing in the fully trained animal is compatible with the view that the same family of neurons is involved again in causing the performance of remembered behaviors.

The main family of neurons in the hippocampus is arranged in a fashion that matches a computer memory grid. Because these neurons also have marked responses to conditioning, we may call them the "memory" neurons. This grid of elements is fed by four different sets of fibers (possibly bringing information to be remembered). Three of these come from the cortex, the drive system, and the arousal system, respectively. The fourth set comes from a neighboring family of neurons (the dentate granules), whose main input is also from the drive system. We call this fourth set the "motive" set of neurons. The drive-system messages thus have both direct and indirect access to the memory grid, but the main drive information is that relayed through the motive neurons—which send their messages only to the memory grid.

Segal's experiments suggest that the activity of the motive set is necessary to *turn on* the memory grid—to make it record—and that later, during playback, memories may need to trigger this motive system in order to evoke behavior.

Three findings pointed in this direction. One was that the motive set of neurons learned first. Early in training, the signal came to cause a briefly delayed acceleration in the firing of the motive neurons. And only after the conditioned stimulus was able to turn on these motive neurons did it begin to influence the neurons of the memory grid. This result intimated that the motive neurons might play a role in turning on the hippocampal learning machine.

This was supported by a second finding. When the auditory signal was associated with punishments instead of rewards, the motive set of neurons became inhibited instead of accelerated. And in this case the memory elements failed to acquire any new response at all. This not only corroborated the view that dentate neurons might be required to turn on the hippocampal learning machine but also added to this concept the hypothesis that these neurons represented the promise of *reward* to the hippo-

campus. This was because they were turned on only by reward signals.

The third finding was that, *after training,* the dentate elements (the motive neurons) fired with a *longer* onset time than the memory set. The anatomical arrangement made this a very surprising finding. The dentate neurons projected only to the memory set. The memory set fired first (apparently acknowledging message number one from the conditioned stimulus). And then after firing, the memory set received a second or reconfirming message relayed through the dentate gyrus. Why was the second message needed; what did it add?

One guess was that the dentate activity at this time might represent in a different guise a central anticipatory process related to reward. After training, the message from the conditioned stimulus would be projected to the memory device. There it would trigger a dry run. This would consist in the playback of recordings (like tape recordings) of behavior sequences related to the stimulus. Those previously followed by reward would as a consequence have connections to the dentate gyrus. The replay of these would therefore activate the dentate elements. These would send a second message to the memory grid which would promote the real activation of the correlated behaviors.

This study of learning has not yet pushed through to the solid outcomes I expect of it. It has guided guesses. But when the number of cases studied is still small, this kind of research gives "iffy" data; a very large number of repetitions will be required to ensure that our observations are real findings. The work has nevertheless validated itself to some degree as a way of attacking the higher functions of the mammalian brain.

It has done this by showing the way to solve some problems posed by conditioning. First, what does training do to the input pathway? The data showed that a conditioned stimulus had its access to the brain facilitated; its input channel was oiled and ready. Explorations to explain this pointed to a changed dynamic process in the cortex. Prior to training there was an ongoing barrage in the cortical area of the stimulus. Training silenced this barrage to some degree. We guessed that the barrage was inhibitory— excluding the signal—and its change to a lower rate by training was itself a "dynamic memory process."

Second, how can we get at other changes that might be ascribed to more permanent growth of new connections? A growth process should take time, and it should not be dependent on continued training. We therefore sought conditioned brain responses that improved not only during training but also during time intervals between training. Experiments were developed in which changes of this kind were easily observed.

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Third, can a small number of recordings from a limited population of neurons get at the intricate workings of machines like the hippocampus. The data showed that the order of changes in the course of learning and the order of firing before and after learning at least helped to organize guesses about these functions.

Conclusion

Will these studies ever turn a corner and begin to offer a kind of answer that has practical value?

My best hope comes from the fact that they are not totally disconnected. Three sets of practical problems confront a teacher. One is related to interest: to turn on the learning machine and to motivate rehearsals. A second is related to temporary memories: to create processes that cause the trainee to see the appropriate things and to act in appropriate ways. The third is to induce retention: to cause the organization and fixation of long-run memories.

If we can put ourselves in a position to observe the activity of the brain during behavioral processes that are closely analogous, I cannot conceive that this will not sharpen our understanding. I do not believe that the wait for practical consequences needs to be interminable.

My final word is in defense of education itself. It is perhaps surprising that any defense should be needed. But current restatements of our knowledge concerning the genetics of intelligence have been misinterpreted so as to imply that they mitigate the importance of educational and environmental factors. The fact of genetic differences in brain hardware is cited as a reason why the manipulable environmental variables cannot solve our basic social problems. Such logic is absurd. Genetic differences require more, not less, improvement in educational techniques; just as a poorer basic computer would need a better programmer—unless you were planning to junk the poor machine, and it is too expensive for that. In the end, it is the programs that determine what any computer will do. And it is education that determines what humans will do. □