# VI

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# The New Neurology: Memory, Novelty, Thought, and Choice

*Karl H. Pribram*

> Thus judgment is a . . . process . . . which is brought about by the difference between the . . . cathexis of a memory and a similar perceptual cathexis. It follows from this that when these two cathexes coincide, the fact will be a biological signal for ending the activity of thinking and for initiating discharge. When they do *not* coincide, an impetus is given to the activity of thinking which will be brought to a close when they *do* coincide.
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> . . . One of the chief characteristics of nervous tissue is that of "memory": that is, speaking generally, a susceptibility to permanent alteration by a single process. This offers a striking contrast to the behaviour of a material that allows a wave-movement to pass through it and then returns to its former condition. Any psychological theory deserving consideration must provide an explanation of memory. Now any such explanation comes up against the difficulty that . . . after an excitation neurones are permanently different from what they were before, while, on the other hand, it cannot be denied that, in general, fresh excitations meet with the same conditions of reception as did the earlier ones. Thus the neurones would appear to be both influenced and also unaltered. . . . We cannot off-hand imagine an apparatus capable of such complicated functioning.
>
> SIGMUND FREUD[10, 11]

Biological scientists the world over have recently turned their heavy laboratory artillery on an age-old problem: the nature of memory mechanisms; event storage and retrieval; learning through novel experience. This interest has, of course, been shared by their colleagues in the behavioral sciences; these investigators have, in addition, readmitted to investigation a field of experimental inquiry that had gone out of fashion for half a century: an analysis of thought processes and of decision-making.

I shall report some of these exciting efforts to you; as academic lecturer I shall take license to weave a tapestry with the data. Bear in mind that other designs, even other fabrics, could be constructed from the same thread—I present my version to demonstrate the rich textures made possible by the new materials with the hope that the particular patterns chosen represent more than mere fantasy. My version of this fabric will evolve from the following four basic threads.

By "memory" I will mean any set of events that makes available to an organism something of a situation after that situation no longer obtains. "Novel" I will define as any aspects of a situation which differ sufficiently from prior situations to produce recordable physiological changes in the organism. By the term "thought" I will refer to the active uncertainty produced when an ordered set of memories mismatches the current novelties of the situation. And "choice" I will use to designate processes of resolution of uncertainty that lead to action. How I have arrived at these meanings will be the substance of this paper. The story begins in the histochemical laboratories of Holger Hydén.

## *Something Old*

### THE NEURON AS RNA PRODUCER

Rats are subjected to rotary stimulation. Rotation is through 120 degrees horizontally and 30 degrees vertically for 25 minutes per day up to 6 days. Microchemical analysis of the nerve cells in Deiters' vestibular nucleus shows a definite and marked increase in the production of respiratory enzymes (cytochrome and succinic oxydases) and in ribonucleic acids (RNA) and proteins.[19] Hydén and his collaborators had, in earlier research, already demonstrated the striking capacity of neurons to increase their production of RNA when artificially excited.[5] In fact, nerve cells have a vastly greater capacity to contain and to produce nucleic acids and proteins than do other cells in the body, so that this characteristic of nerve tissue is as conspicuous as is their ability to generate and transmit electrical potential changes.[17] The well-known role of the RNA molecule, together with its more stable sister substance, DNA, in the mechanisms of genetic "memory," stimulated the suggestion that RNA is somehow involved in the mechanisms of neural memory. But before the question "How?" can be properly posed, other observations and experiments must be detailed.

### THE CONSOLIDATION HYPOTHESIS

Remembering is not always intensive activity; periods of rest may greatly enhance the effect of the waking effort. Consider also the retrograde amnesias commonly observed in conjunction with severe head injuries. Memory traces appear to require time to fix in the brain. This fixing process has been called consolidation and subjected to a good deal of recent experimental analysis.

The common method for producing retrograde amnesia in the laboratory is to administer electroconvulsive shock to rats. There is considerable evidence that the sooner after an experience the convulsion occurs, the greater is the interference with later performance relative to that experience. For instance, Duncan[9] found a maximum effect when convulsions followed an avoidance trial within 15 minutes; the effect is practically gone when an hour intervenes between the conditioning trial and the convulsion. There are some results, however, which do not neatly fit a straightforwardly simple consolidation notion.

Poschel[35] gave rats a two-day series of electroconvulsive shocks at the rate of five per day. The rats were trained to run an alley maze to a goal box that contained food. During the convulsive series, however, the rats experienced shocks to their feet in the goal box. Half of the subjects received the convulsions *prior* to the foot-shock experience; for the other half it *followed* the experience in approximately 24 hours. No differences were found between these groups, though both avoided the goal box significantly less than did their controls. The effect of the convulsion was, therefore, as much proactive as retroactive. An experiment by Brady[3] made use of the "conditioned emotional response." With this technique, a subject is taught to press a lever for a food-reward presented at intervals varying about some average period of time. A signal is turned on somewhere during the performance and this signal is invariably followed after a given time by a foot-shock. As a rule, the subject's response radically diminishes, or response ceases entirely while the signal is on. A normal rate of response is resumed once the shock has been experienced and the signal is off. In Brady's experiment, a series of 21 convulsions at the rate of three per day was begun 48 hours after the last conditioned emotional response trial. Testing was resumed four days after the completion of the convulsive series—all convulsed subjects failed to react to the signal at this time. Without further experience with the task, however, retests at 30 days after completion of the convulsive series showed recrudescence of the conditioned emotional response—and this performance was maintained on retests at 60 and 90 days. These experimenters, as did others, exceeded the crucial hour during which the consolidation process can be maximally affected—their results indicate, however, that some mechanism necessary to the retrieval of the memory trace is still fragile for as long as a day or two after an experience.[*]

McGaugh felt that if the consolidation hypothesis is to be taken seriously one ought to be able to find techniques to *improve* learning and not rest solely on demonstrations that remembering has been interfered with. He discovered an early work of Lashley's[23] where small doses of strychnine sulphate were found to facilitate learning in rats. Together with Petrinovich, McGaugh repeated the study.[28] Seventy-six rats were trained in a Lashley III maze. Each day 33 experimental subjects were injected with 1/3 to 1 mg./kg. of strychnine sulphate ten minutes prior to receiving five maze trials. Controls were injected with the normal saline. All subjects were tested to a criterion of five correct out of six consecutive trials. The controls averaged 46.9 errors in attaining criterion while the strychnine-injected animals averaged only 29.2 errors, a highly significant result.

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[*] The suggestion has been repeatedly made that the retrograde amnesic effects of convulsions can be totally ascribed to the production of "fear" in the subjects.[7, 13, 23, 42] Madsen and McGaugh[26] have replied to these assertions with a simple experiment. They placed rats in a box on a raised platform. Both box and platform were covered with copper sheeting. The platform was then slowly lowered and when the rat stepped off, it completed the circuit and received a foot-shock. Half the rats were then given a convulsion within 5 sec. of the time they stepped off the platform. After 24 hours all rats were again placed on the platform and the platform lowered. Almost all of the convulsed rats stepped off, whereas only about half of the controls did so. Another direct test of the fear hypothesis has been made by Pearlman *et al.*[34] They taught rats to press a lever, then electrified it. Now lever-pressing resulted in foot-shock and the rats avoided the lever. If the rats were convulsed (with Metrazol) they returned to lever-pressing 100 per cent provided the convulsion occurred within 10 sec. after the foot-shock. In addition, there was significant impairment of retention when the convulsion occurred for as long as four days after the foot-shock trial. In this case the subjects went back to lever-pressing at 70 per cent of their prefoot-shock level, compared to 1 per cent for the nonconvulsed controls.

In a subsequent study, McGaugh[29] injected the strychnine sulphate solution 30 sec. after each trial—again highly significant results were obtained in favor of the strychnine-injected rats. Petrinovich extended these findings to discrimination learning; McGaugh and his students to other types of mazes, and so on. In addition, McGaugh and his co-workers[30] replicated and extended the experiments using picrotoxin and a new strychninelike-acting drug, diazadamantan, obtained from Daniele Bovet of the Istituto di Sanità in Rome.

These investigations uncovered one other interesting result that may have some practical applications. Some of the research was performed with two genetically different strains of rats—the one fairly "bright" in learning mazes, the other rather "dull." In some of McGaugh's experiments intertrial interval was simply varied, and in others drug injections and convulsions were juxtaposed to both massed and spaced trials. The results demonstrated that the maze-dull rats were dull because they took longer to consolidate the effects of each trial experience—e.g., spacing trials improved the performance of the "dulls" but not of the "brights"; convulsions administered 45 sec. after a trial affected both the "brights" and the "dulls" while such convulsions given 30 minutes after a trial affected only the performance of the "maze-dulls."

These experiments form an impressive body of evidence that some consolidation process must occur in laying down the memory trace. The brain must be involved in consolidation—but how?

In our own laboratories[14, 22, 36, 44–47] different areas of the brain cortex of monkeys have been treated with aluminum hydroxide cream to produce local irritations manifested by altered electrical activity (abnormal slow waves and spike discharges). Such irritative lesions, while they do not interfere with monkeys' capacity to remember the solution to problems repeatedly solved prior to the irritation, do slow their original learning of these problems some fivefold. Moreover, problem-solving in general is not affected; the defect is specific for those solutions to tasks which cannot even be remembered when that particular part of the brain has been removed. These results can be interpreted to suggest that such irritative lesions delay the consolidation process. A test of the suggestion would come from a comparison of learning by irritative-lesioned monkeys under spaced and massed trial conditions. Tentatively though, for the present purpose, the indication can be accepted that irritation with aluminum hydroxide cream interferes with memory consolidation.

Could the irritative lesion in some way alter the neural tissue's production of RNA and thus affect the memory mechanism? Chemical analysis of the tissue implanted with aluminum hydroxide cream would be messy, to say the least. Nonetheless, an ingenious answer to this question has been achieved by Morrell.[31, 32] He based his experiments on earlier reports that an irritative lesion made in one cerebral hemisphere produces, after some months, a "mirror focus" of altered electrical activity in the contralateral cortex by way of the interhemispheric connections through the corpus callosum. This "mirror focus" has not been directly damaged chemically, yet it possesses all of the epileptogenic properties of the irritative lesion. Morrell ascertained that the RNA in this mirror focus was considerably altered when compared to that found in normal brain tissue. The notion that RNA production by nerve cells is in some way involved in memory consolidation becomes somewhat more persuasive. However, the question of mechanism remains.

### THE NEW NEUROLOGIA

To return to Hydén's laboratories: brain tissue is composed of two sorts of cells, neurons and glia. Glia were hitherto believed to serve only as support and nutrient for the all-important neurons. But recent evidence suggests that at least one type of glia, the oligodendroglia, which completely envelops neurons, functions with them as a glia-neural couplet both in the generation and modulation of electrical potential change and in the production and utilization of RNA.

Hydén[18] gently teased apart the neurons and the glia of the vestibular nucleus. He found that the increased production of RNA in nerve cells concomitant with their excitation was coupled with a simultaneous decrease in RNA concentration in oligodendroglia. During this period of excitation glia could provide the nerve cell with energy-rich compounds since the glia apparently resort, at least in part, to anaerobic metabolic routes such as glycolysis and lipid breakdown. In addition, however, Hydén finds that after excitation ceases, the glia in turn increase their RNA production while that of the adjacent neurons diminishes. On the basis of other experiments, Hydén suggests that the aerobic-anerobic balance is maintained through competition for inorganic phosphates (the Pasteur effect), with the respiratory phase of the process dominant over the fermentative glucose degradation, and the phases in the neuron dominant over those in the glia. This phase lock-in mechanism is assumed

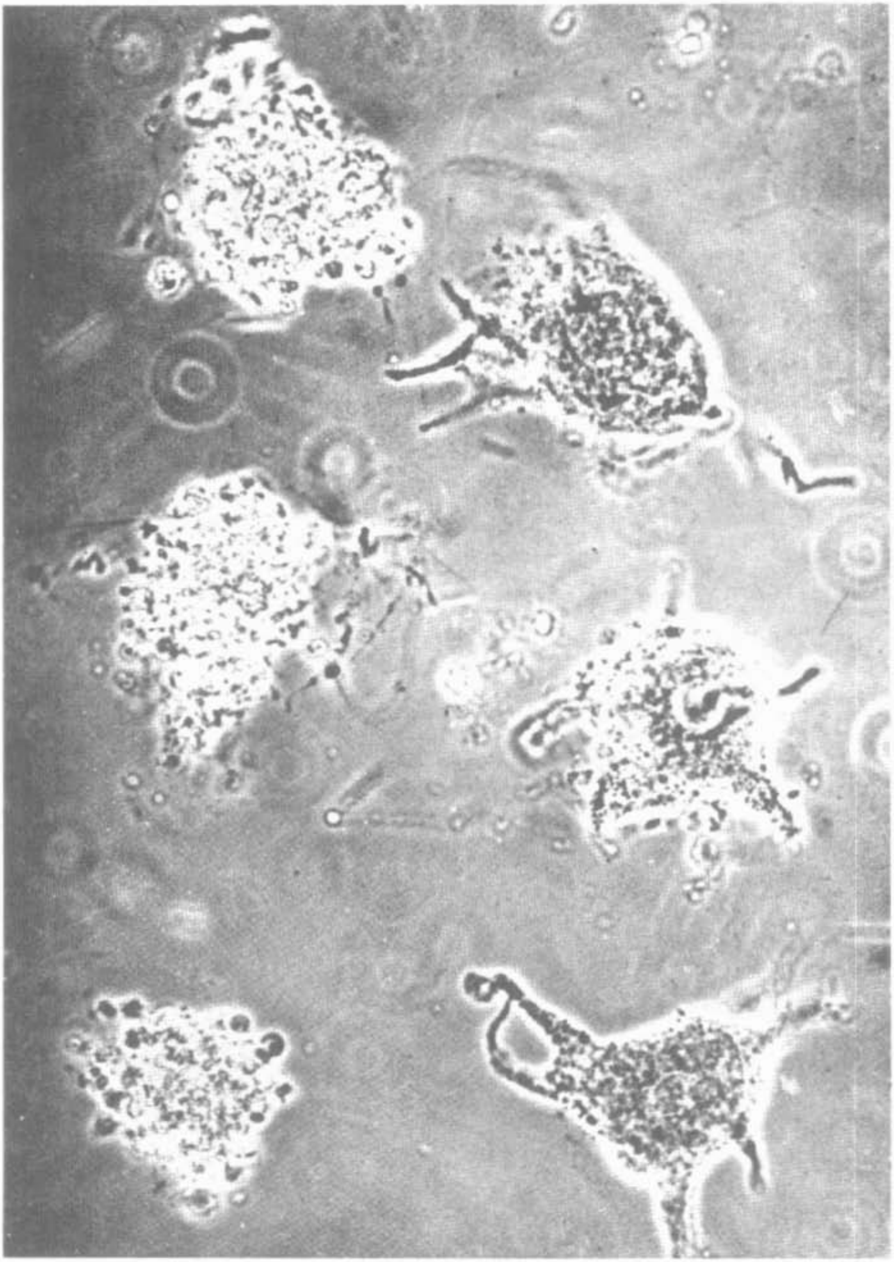

Fig. VI—1. *Neuron and glia teased apart.*

to operate through pinocytosis. There is ample evidence of possible pinocytosis from high resolution analyses of the structural arrangements of the glial-neural border. In addition, pinocytosis has been observed in glia and nerve cell tissue cultures where it can be induced by electrical stimulation.

Why this fuss about a glial-neural couplet? There are several reasons. For one, glial cells reproduce, while neurons do not. Should the memory storage mechanism turn out to be related to protein synthesis guided by RNA production, such stored protein could be replicated by glial cell division.

Second, nerve cells must remain constantly ready for new excitation. The time course of the effects of excitation is short, even when nerve nets rather than neurons per se are considered. In simulated nets, the difficulty has been to adjust the time an element "remembers" in such a fashion that "learning" can take place. Either the net remembers everything too much and so very quickly ceases to be sensitive to new inputs, or else in the process of retaining sensitivity, so little is remembered that learning can hardly have been said to occur. This difficulty can be overcome in simulated "memistors" by adding a longer time-course storage device which sets a bias on the reception of new inputs and is in turn itself altered by those inputs.[51] The glia could function in this fashion. Even their electrical responsivity is some thousandfold longer in duration than that recorded as impulsive activity from neurons. There is every reason to suppose that such graded electrical activity would influence the transmitted excitations of the adjacent neural net, which in turn, through the phase lock-in biochemical mechanism, could alter the state of the glia.

In any event, these processes take time: the time demanded by the consolidation hypothesis. But, as already indicated, the evidence on consolidation is not uniform. There appears to be one process that takes no more than an hour and reaches a maximum some seconds after an experience. When this process is interfered with, recall is obliterated. There is another process, taking hours and even days, which, when interfered with, produces only temporary amnesias with practically total spontaneous recovery of performances based on the experience obtained prior to the interference. This second type of evidence cannot be easily fitted to the electrobiochemical explanation of the memory mechanism so far proposed. Some process must be sought that has a longer duration and is more resistant to permanent interference yet in some ways is temporarily more fragile.

### RETRIEVAL THROUGH NETWORK GROWTH

Though the brain's nerve cells do not divide, they can grow new branches. This has been dramatically demonstrated[39] in a study of the effects on brain of high-energy radiations produced by a cyclotron. Minute, sharply demarcated laminar destructions (often limited to a single cell layer, and this not necessarily the most superficial one) were produced in rabbit cerebral cortex when high-energy beams were stopped short by the soft tissue. The course of destruction and restitution was studied histologically. Intact nerve cells were seen to send branches into the injured area; these branches became progressively more organized until, from all that could be observed through a microscope or measured electrically, the tissue had been repaired (Figure VI–2).

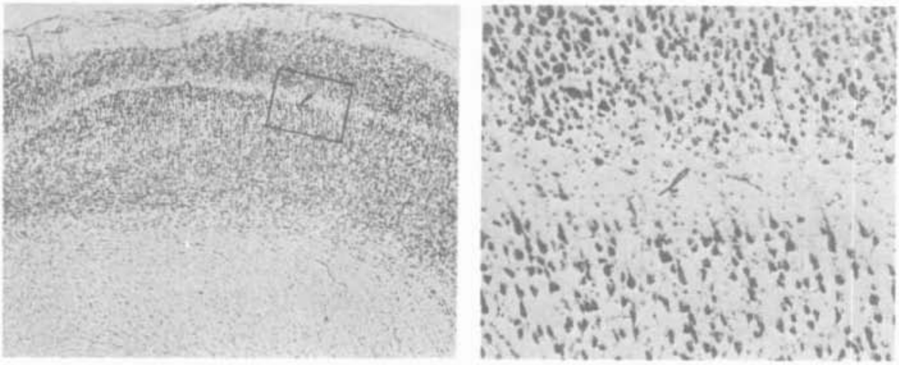

**Fig. VI—2.** *Laminar destruction in rabbit cerebral cortex produced by high energy radiation.*

The organization of the branches of nerve cells could well be guided by the glia that pervasively surround these branches. Such directive influences are known to be essential in the regeneration of peripheral nerves. Schwann's cells, close relatives of glia, form a column into which the budding fibers must grow if they are not to get tangled in a matted mess of their own making.

The assumption is that glial cell division is somehow spurred by those same activities recounted above as important to memory storage. The resulting pattern of the glial bed would form the matrix into which nerve cell fiber growth occurs. Thus guided, fiber growth is directed by its own excitation—the whole mechanism based, however, on the long-lasting intervention of glia. The mechanism would account for the later interfering effects obtained in the consolidation experiments and in the spontaneous "restitution" as well: the growing nerve cell fiber is ameboid and can temporarily retract its tip which is made up of a helical winding of small globular protein molecules. After the convulsive insult is over, first tentative, then more vigorous probings can again be resumed in some "random-walk" fashion by the nerve fiber tip as has been suggested for normal growth by von Foerster.[49] The glial substrate, assumed undamaged, will perform its guiding function to effect the apparent restitution.

The glially guided neural growth hypothesis, in addition to accounting for these late interference effect data, has another attractive feature. The electrochemical memory storage process per se has built in no satisfactory mechanism for information retrieval. A neural network structured through growth, glially guided by experience, could serve retrieval much as do the "feelers" on the magnetic memory core of a computer. The patterns of electrical signals that activate particular network configurations would correspond to lists or programs fed to a computer and to the schemata proposed by Bartlett[2] to account for the results of his studies on memory in man.

### TISSUE EFFECTS OF EARLY SENSORY DEPRIVATION

Is there any evidence to support directly these notions about the memory storage and retrieval process? Most persuasive are the as yet meager results of histological and histochemical analyses of neural tissue obtained from animals raised under conditions of sensory deprivation. In the normal subject a considerable growth in the number of cellular and fiber elements takes place during the first months after birth[6] (Figure VI–3). This is associated, as would be expected, by production of substantial amounts of RNA.

Weiskrantz[50] has shown that in the retinas of dark-reared kittens, Mueller fibers are scarce—and Mueller fibers are glia. Brattgård,[4] Liberman,[24] and Rasch *et al.*[38] have all shown deficiencies in RNA production of the retinal ganglion cells in such dark-reared subjects. These are initial forays—they do indicate that even for mammals the techniques are available for a direct attack on the memory problem.

### REGENERATE WORM-RUNNERS

Meanwhile, experiments by a group of "worm-runners" have added fuel to the RNA fire. Flatworms (Planaria) were trained by McConnell

**Fig. VI—3.** *Stages in the developing human brain (Drawing from Golgi-Cox; after Conel.)*

*et al.*[27] in a water-filled trough illuminated from above. The animals were placed in a trough until they showed no reaction to the turning on and off of the light. Then each illumination of 3 sec. duration was accompanied for the last second by an electric shock passed through the water. Initially the worms contracted and turned only when the shock was on; gradually, the frequency of such responses increased during the first 2 sec. when only illumination was presented. Once a worm had reached criterion it was immediately cut in half transversely, the halves isolated and allowed to regenerate. About a month later when regeneration was complete, all subjects were retrained to the original criterion; whereas original training averaged 134 trials, subsequent to transverse sectioning, the original head ends averaged 40 and the original tail ends, 43.2 trials. (A trained but uncut group showed about the same amount of savings; a group trained after the cut took more trials than did the original group's initial training; thus a sensitization effect was ruled out.)

On the basis of these and other similar results, McConnell and his collaborators suggest that whatever the physiological change responsible for this memory process, it must occur throughout the worm's body. Corning and John[8] tested the hypothesis that RNA may somehow be involved in this mechanism. They immersed the halves of the trained worms in a weak solution of ribonuclease in order to destroy the RNA. The heads regenerated in ribonuclease showed savings as great as control heads; on the other hand, tails regenerated in ribonuclease showed no such savings. The brain-stored memory mechanism was apparently resistant to this exposure to ribonuclease, whereas the somatically mediated "worm memory" was destroyed.

Thus, the evidence for a dual memory mechanism accumulates: both an RNA-protein synthesis and a glially guided neural-growth process have to be taken into account in descriptions of how organisms react to "something old"—situations that no longer obtain.

## *Something New*

### HABITUATION AND NOVELTY

An entirely different series of experiments serves to link this elementary memory-trace mechanism to thought. These experiments show that at any moment current sensory excitation is processed by the memory trace which forms a representative record of the minute details of prior experiences. It is the match or mismatch between current excitation and this representative record that guides attention and action.

Sokolov[43] performed the following simple demonstration. A person is exposed to the beep of a horn: he ordinarily turns toward it. The electrical activity of his brain displays a characteristic "alerting" pattern—activation of the record obtained from the lateral cortex, especially the region of the auditory projections, and hypersynchrony of the record obtained from medial and basal forebrain structures such as the hippocampal formation. Additional physiological characteristics of orientation can be identified. The flow of blood to the head increases at the expense of flow to the fingertips; changes occur in the electrical resistance of the skin. Should the horn beep be frequently repeated, all these reactions gradually diminish and finally practically die out. The subject is said to be *habituated* to the stimulus.

The lack of reaction to the continuing beep is deceptive, however. Actually a great deal is still taking place. For if the smallest change is produced in the stimulus, such as a softer beep, all of the initial alerting reactions recur. Sokolov interpreted this to mean that the person must be matching the current sound against a stored representation of prior horn beeps—else why would a diminution in intensity call forth the full-blown orienting response? He tested his interpretation by habituating the person to a tone of a certain length. Then, suddenly, a shortened tone was presented. Now orienting reactions occurred when the tone ceased, i.e., alerting responses were recorded with the onset of silence. The reactions continued for the "expected" length of the tone, then slowly disappeared. We have all experienced this surprising reaction to sudden silence.

Only a few of the neural events that partake in habituation are known; the course of build-up of a central representative process against which input is matched has only begun to be analyzed. There is considerable evidence of the specificity of the buildup.[12, 15, 41] The process appears to be more rapid in nonmodality-specific than in modality-specific structures.[21] Attention to a noise diminishes the neural response to a flickering background light for the duration of the attention.[16] This match-mismatch mechanism, so intimately a part of the attentive process, is mediated in part at least through efferent control, exercised by central structures over their own afferent input. The evidence for such central regulation of input has been repeatedly reviewed in recent years.[25, 37] One need point out here only the important fact that this mechanism provides a way for gradual self-regulated modification of central processes. Modification follows mismatch. If input matches the central representation completely, neural habituation is established with concomitant behavioral inattention and boredom. Inputs completely outside the experience of the organism may be equally excluded from influence on behavior through efferent gating. Most effective guides of behavior are inputs but slightly dissimilar to prior familiar inputs. Such novel inputs mismatch —and so produce all of the consequences of mismatch.

To put it in another way, were there no memory mechanism, no representative record, we could not recognize novelty or similarity. Thus we could not direct our actions in an orderly way. In a creature without a self-modifying match-mismatch mechanism, the enormously potent intensity of momentary occurrences would make haphazard demands on attention and action so that no course could be charted between the Charybdis of disruptive differences and the Scylla of stultifying sameness.

### ERROR

It is this capacity to sense sameness and difference between recurring events that is also the basis for the detection of errors made in solving problems. Again, the laboratory has given us a beautiful demonstration—this time the laboratory of Adey.[1] The subjects were cats. Fine wires were inserted into the depth of the brain and tied to the skull so that they could do no harm. The cats were placed facing a Y-shaped raised drawbridge. At the ends of the arms of the "Y" were two boxes about a yard apart, one of which contained food. As a flashing light was turned on above the box with the food, the drawbridge was lowered to form a path to each box.

During the first exposure to this situation, electrical recordings made from the brain of the cat disclosed the characteristic pattern of alerting. With repeated exposure the recordings showed increasing habituation. Since the cat began to expect food when she reached a box, the alerting pattern occurred only when she had chosen the empty box. The cat's performance can be judged as reliably from the recordings as from her observed behavior.

This alerting and error-sensing are manifested by changes in the patterns of electrical activity made in the brain. These changes are dependent on the presence in the brain of a detailed record representing the effects of prior stimulation—a record conceived as composed of RNA-induced protein molecular change and, additionally, the progressive growth of nerve fibers guided by glial cell division. This record is matched against the effects of current excitation—a match results in habituation, the sensing of similarity; a mismatch in alerting, therefore in novelty and error-sensing.

## *Sometimes Thoughtful*

### UNCERTAINTY

Still more interesting, during the latter part of the drawbridge experiment when the cat's performance had become excellent, the electrical activity that accompanied error often occurred *before* the cat had had an opportunity to search the empty box. Actually, the "error patterns" began the moment the cat headed down the wrong path and, occasionally, some instants before. Her behavior reflects her uncertainty. If the cat could talk, she would probably say, as humans so often do after making an error, "All along I thought that something was wrong."

Since people can report on their thoughts, patterns of electrical activity of the brain can be related to thinking. For instance, when one ponders a mathematical problem, the entire brain wave record becomes choppy. Should one think merely of solving a manual puzzle, the choppy pattern is restricted to the part of the brain that directly controls the hand's actions. Different areas of the brain can be involved when different solutions are entertained.

### PROBLEMS AND PROBLEM-SOLVING

How are match-mismatch mechanisms of our brains used? How are problems faced—how are problems made—how is uncertainty actively engaged? Experiments with monkeys[37] have given additional leads as to the nature of the matching process in use. A simple situation was devised to produce uncertainty. It resembles the popular shell game. A peanut was hidden according to some rules under one of several objects placed on a board. The monkey was allowed to choose among objects—he was allowed only one choice at a time. To all appearances, the monkeys seemed to be thinking when faced with the alternatives. They often reached tentatively toward an object only to withdraw, scratch their heads, and pause before the response was finally completed. One monkey, incredibly, sat before the confusing objects, elbow on knee, chin cupped in his paws, a furry, charmingly alive miniature of Rodin's famous statue, "The Thinker."

Groups of these monkeys had had brain operations which influenced the way they played the game. One operation—removing the inferotemporal cortex—changed the way the monkeys proceeded to search for the peanut. Another operation—removing the anterior frontal cortex—had no effect on the strategies of search but prevented the monkeys from following an obvious lead, that is, sticking to the object under which they first found the peanut. Almost anything distracted this group of monkeys. At times they seemed to make their own distractions, reminding one of a bored high school student doing homework; like the student, the monkey reacted swiftly to any change, any novelty introduced into the situation.

How a given problem is solved depends therefore on how it is searched and how a particular viewpoint is maintained in the face of alternatives. Should the memory traces be held too rigidly inviolate, nuances would never be remembered and the problem would become insoluble. The inflexible memory traces resist influence from the new situation; a match is never achieved. Inflexible sameness of thought results. On the other hand, habituation can be too evanescent, the memory traces can be held too lightly and changed by incidents which, though temporarily remembered, are displaced too soon by others. Then thinking is fleeting and disorganized. Each of these conditions has its counterpart in daily experience; each can be produced by a specific brain operation limited to one of the so-called "association areas," but as yet there is no clue as to how these brain operations wreak their havoc. Anatomical and electrophysiological experiments are sorely needed to trace the connections from these "association areas" by which they exert control over the activities in the projection areas.

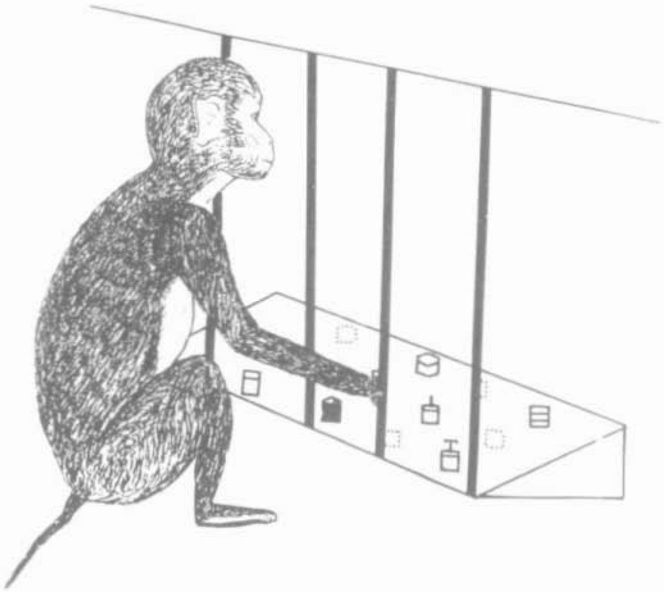

**Fig. VI—4.** *Rhesus monkey playing the multiple choice game.*

Meanwhile, much can be learned from a more direct approach to "thought" by both an in vivo and an in vitro analysis. For this purpose, monkeys will not do. People are needed when any but the most rudimentary of thought processes are to be studied; and when these processes must be manipulated, the behavioral science counterpart to the test tube, the computer, becomes indispensable.

People have an advantage over monkeys; people are able to express their thoughts. Through language their thoughts become inputs to others, and even to themselves, inputs which have the power to influence memory through the match-mismatch process, and so to alter further thinking. Indeed, the processes that govern the development of language in the infant are roughly the same as those involved in the development of thinking. The power of language is achieved slowly, in stages. Once an infant has passed the babbling stage, he notes the effect of the sounds he makes in the game he continually plays with his parents or some other child. Gradually he comes to remember and to bring to the game certain strategies, such as make raucous sounds for immediate attention; for prolonged play, a more gentle tone. These initial strategies quickly lead him to appreciate subtleties. "Mama," for example, will evoke a parent different from "Papa." Then the child is ready for a stage monkeys never achieve. He identifies his thoughts and expresses the identification. He does this by acknowledging the difference between the excitation in his brain produced by the current situation and the memory-trace record. He distinguishes objects from their previously acquired meaning and use to him. He knows "Mama" (object) is for feeding (meaning); the dog for petting; a hole for digging.

The child is now ready to meet the rules for speaking—the forms and usages that allow effective interchange with others. He is alert to the subtleties of language, and so language becomes his primary tactical tool for communication with himself—that is, for thinking.

### PROGRAMS, PLANS, AND ORDERED COMPLEXITY

The utility of language as a tool of thought is perhaps most clearly demonstrated by that very special tongue, mathematics, and when logical mathematical processes are in question, those modern "thinking machines" (the electronic computers) come into their own. The algebra or logic they use in solving problems is built into programs by procedures similar to those that characterize all thinking. First, some rules are set down to establish the outline of the problem—for instance, the rules of chess or of compounding interest on savings. The computer "learns" these rules, that is, stores them in its "memory." Next, specific information—moves in chess, the number of dollars deposited—are fed into the computer. But the description of this information must be couched in terms the computer can understand—terms that match the appropriate rules so they can be summoned from storage. Only then can the information be processed and a solution achieved. Usually, the solution is relatively crude: a checkmate ends the chess game after only a few strategically simple moves; interest is compounded on the amounts on deposit as of 1 January each year. For greater sophistication new rules are added, programming the input of information within the context of the already established rules. The order of moves in the chess game is now based on instructions from a chess master; interest is computed first on a monthly—later on a daily—basis. These secondary tactical rules, or subroutines, have the same relation to the initial rules that subheadings have to the major items in an outline. The writing of utilizable outlines by computer programmers is much the same sort of task as making an outline for a theme in an English course, except that, since the computer's theme will never actually be written except in outline form, the program has to embody seemingly infinite, meticulously constructed detail.

The striking similarity between the way people think and a computer computes suggests that our brain organizes, "plans," our behavior much as a computer goes about solving problems.

Thus far, the discussion has ranged over several kinds of thinking, from the repetitive, rigidly fixed to the fleeting, poorly organized, to which everyone is at one time or another prone. Both kinds can result from damage to certain parts of the brain. In between is the more usual, productive kind of thinking, the thoughts being flexibly coordinated with the task to be performed within a structure outlined by experience. But what about creative thinking? As yet, no computer has achieved it. Are the characteristics of creative thought so mysterious as to defy understanding? Perhaps not.

Perhaps we harbor many misconceptions about creative thinking. According to the most prevalent conception, discoveries and inventions arise out of the blue; but the contrary is the case. In reality, discoverers make their discoveries through what they already know: they match the unfamiliar against a thoroughly incorporated body of fact. Columbus, for example, knew a great deal about navigation. He knew the assumed boundaries of a flat world and what could be expected if, as some people suspected, the world was really round. But other explorers had to repeat Columbus' feat before the discovery of America was admitted (should we say as a subroutine?) to the thinking of all sailors.

The inventor achieves novelty within the bounds of certainty. He comes upon, finds, only when properly prepared for the finding. The term "inventor" derives from the same root as "inventory." Edison expended his "ninety-nine per cent perspiration" by taking stock of the boundaries of known electrical science. Only then, at those boundaries, did new procedures strike him as plausible. The inventor innovates, as when, like Edison, he substitutes tungsten for iron to make an electric light bulb from an electric heating element.

The construction of a great symphony follows familiar lines: the rules of theme and subthemes, beat and counterpoint, form and movement, must all be thoroughly mastered before creative composition can begin. Beethoven created music by taking discipline even further than its already complex structured limits. He sensed nuances where none had been sensed before. He prepared musical programs more complicated than seemed possible.

And what of the poet, supposedly the freest of free souls? Perhaps more than any creator he is constrained by the known rules within which novelty can be expressed. Shall he choose iambic pentameter, rhyme or alliteration, couplet or sonnet? He must carefully tend the meaning of a word so that where several meanings are possible each is enhanced by the context in which the word appears. In such a wealth of rules and orderliness lies the creativity of the poet as well as his freedom. For freedom is not anarchy. Real freedom is intelligent, knowledgeable choice and rises out of order when order achieves sufficient complexity.

## *But What To Do?*

### THE TEMPORARY DOMINANT FOCUS

And so we are left with the problem of how choices among alternatives are possible; how thought, active uncertainty, ceases and action is engaged. Again we turn to the nervous system. One of its properties appears to be that, under the proper circumstances, a more or less temporary dominant focus can be established. John[20] reviews the literature relevant to this property. Experiments of the following sort have given rise to the concept. Early workers had established a conditioned avoidance response by pairing a metronome beat with a shock to the left rear paw of a dog. They then placed a small piece of filter paper soaked in strychnine on the part of the motor cortex that primarily controls action of the right forepaw. Following strychninization, presentation of the metronome beat elicited vigorous flexion of the right forepaw rather than the left rear. The chemically induced excitable focus dominates so that the afferent input which had previously been processed on the basis of experience in the situation now initiates a response consonant with the chemical manipulation.

Ukhtomski[18] is responsible for the concept and term "dominant focus." He characterized it as a (1) relatively heightened excitability of a group of nerve cells leading to summation of the excitations arriving from a variety of sources, and (2) a retention of this excitation once it has been established, thus leading to a capacity to continue a stable discharge when the original excitations have disappeared. In the presence of a dominant focus, therefore, the normally random distribution of excitation with a population of nerve cells would be altered to a massive response synchronized to the discharge of cells of the focus. Recently, the turn of investigation has centered around the production of such dominant foci by D.C. polarization of neural tissues applied during learning.[32, 40]

### PATTERN FOR DECISION

John,[20] in his review, goes on to show how this process if repeated often could lead to the establishment, in the nervous system, of the representative records of repeated inputs. The discussion has come to full turn. But, of equal interest is the fact that the dominant-focus experiments provide a mechanism that accounts for choice among representations already established. Such a mechanism would be composed of a temporary *pattern* of dominant foci. These would mobilize and give precedence to a particular order of activation of the neural network configuration (plan or program) among the several that partake of the same stored structures.

The process involved is perhaps made most readily understandable by recounting one of Warren McCulloch's favorite analogies. Military organizations have employed two essentially different types of organization. One common type is characterized by a pyramidal system of communication and control. Communication goes up; decisions are made at the apex and handed back down for execution. The second type is of interest here. Navies have used it to a considerable extent since the Battle of Jutland. Organization is pyramidal much as in the first type. In this case, the pyramid is made of a system of rules rather than decisions, initiated at the top and communicated down. In addition, communication is allowed to take place horizontally. Any input to the organization is therefore transmitted in all directions. Wherever the input intersects a rule, a decision node is formed and this node takes command of the organization. For example: a rule, known to all members of the organization, states that when 100 or more enemy planes are sighted, the fleet is to withdraw; that 99 or fewer planes are to be attacked. The seaman who spots, counts, and immediately communicates (e.g., to the ship's radio operator) information about the strength of an enemy squadron has to all intents and purposes temporary command of the fleet until that squadron is engaged or disengaged. A node of decision—a dominant focus—has temporarily been embodied in that seaman and his immediate communicants.

According to this scheme, *choice* is determined by the interaction of sets of learned (and inherited) constraints on the randomness of neural activity with current inputs from the environment. These inputs must be sufficiently similar to the constraints to engage them, yet be dissimilar enough so as to be distinguishable as uniquely current, i.e., *novel.* Where these novel inputs and the systems of constraints, e.g., the memory structure, intersect, they form temporary *patterns of dominant foci.* These patterns, in turn, determine which of the systems of constraints is activated. While a pattern of such dominant foci is being formed, *active uncertainty exists*—in man this active uncertainty is expressed as *thought.* Once such a pattern of dominant foci has activated the system of constraints, the *record of experience* is augmented both by *biochemical change* and by *glially directed fiber growth.* Storage and accessibility, thus both assured, ready the organism for new novelties, further thoughtful uncertainties and the experienced wit to choose.

The brain, as more and more experimenters find, is truly made to accomplish what it must, behavior being what it is.

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