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The Four R's of Remembering

by Karl H. Pribram

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Introduction

The four R's of remembering, which I want to discuss, are representation, reconstruction, registration, and rearrangement. All of these, as well as "remembering" itself, begin with "re"—a prefix that denotes repetition. To say that the educational process involves repetition may seem self-evident, but a fresh look at the variety of forms that repetition can take is in order. In fact, the study of the structure of repetition reveals an unsuspected richness and importance that has, for the most part, been ignored in scientific investigations.

The technical term for repetition is "redundancy." The concept is derived from information-measurement theory, which for the past two decades has contributed many of the major advances in thinking about problems in the behavioral sciences. Most of these have come from the precision given the term "information" by communications engineers and their ability to construct computers—devices that process information. "Information" conceived in this fashion is akin to what in ordinary language we mean by "novelty"—with the provision that novelty almost always refers to something new about something familiar (as expressed, for example, by the fact that the words "invent" and "inventory" stem from the same root). The recent concern in the behavioral sciences has been with information measurement, information processing, and even information storage. And so, in teaching and learning, the emphasis has been on ways of imparting the novel, the facts, the latest facts, to our students. Because the computer can handle masses of such facts, the major question persistently posed of educators in this post-Sputnik space age has been: how can

we make our students into better "computers"—i.e., better information-processing organisms?

This approach has, to my mind, missed half the problem. Wolfgang Köhler once wrote a book entitled *The Place of Value in a World of Fact* (27). In this spirit, perhaps I should have entitled this paper "Redundancy in a World of Information" or, better yet, "Memory in a World of News." The point is that values, redundancy, memory—the enduring aspects of the world we live in—have been given short shrift of late in our scientific thinking. Every psychologist who has explored the problem has found that the context, the set of events in which information occurs, is as important a determinant of the outcome of his experiment as the information-carrying signal itself. And yet it is usually this context that remains unspecified, unstudied, and often hopelessly shrugged off as being impossible to study.

Why? Most likely because the enduring is so often carried in the organizational system of an order higher than the one the scientist is studying. Culture is enduring—culture carries values and is endowed with memory. Behavioral scientists of the hard-headed variety rarely want to take such a large system into account, for this would only point up the limitations of their data. Organisms also endure and so bring values and memories to each situation, whether it be a classroom or a conditioning experiment. The behavioral scientist already has enough to think about—this complex biological organism is altogether too much. Yet, as so clearly sensed by those who have invited us here, how can we be successful educators when we know not the capacities of those whom we are trying to lead, or, for that matter, out of where we are leading them?

The work of my laboratories has, over the past two decades, been devoted to unraveling some of the mysterious organizations educators try to educate. These studies of brain and behavior indicate that there are at least two major classes or modes of organization into which repetitiously experienced events are coded. Each of these encoding processes appears to be intricately interwoven with another that decodes and makes usable the memory mechanism involved. I will adduce some of the evidence for the existence of each of these four processes (representation, reconstruction, registration, rearrangement) and suggest a model for each of the two memory mechanisms (spatial and temporal) by way of analogy with an operational physical artifact whose characteristics have been independently studied.

*Representation: A Spatial Encoding Process**

Let me begin by detailing an apparent paradox concerning habit and habituation. If we are repeatedly in the same situation, in a relatively invariant environment, two things happen. One is that if we have consistently to perform a similar task in that environment, the task becomes fairly automatic—i.e., we become more efficient. We say the organism (in this case, *ourselves*) has learned to perform the task; he has formed *habits* regarding it. But at the same time the subject habituates, by which we mean that he no longer produces an orienting reaction; he no longer notices the events that endure, are constant, in his environment. His verbal reports of introspection, his failure to move his head and eyes in the direction of the stimulus—electrophysiological measures such as galvanic skin response, plethysmography, and EEG—all attest to the disappearance of orienting with repetition of unvarying input in an unvarying situation.

Habituation, however, is *not* an indication of some loss of sensitivity on the part of the nervous system. Sokolov (56), for example, has demonstrated that if he decreases the intensity of a tone that has been given repeatedly to a subject, orienting or alerting will recur. Further, if he again habituates the subject and then shortens the duration of the tone, orienting again will take place, but this time to the unexpected silence. These findings led Sokolov to propose that a neural model of the environment is produced in the nervous system. This model then constitutes an expectancy, a type of memory mechanism against which inputs are constantly matched. The nervous system is thus continually tuned by inputs to process further inputs.

It is hardly necessary to state that the habitual performance of the organism is also due to neural activity. The point to be kept in mind is this: in the case of expectancy, there is a diminution of neural activity with repetition, while in the case of performance, enhancement seems to occur. So the question becomes: what is the difference between these two kinds of neural activity that appear at first sight to be

* The biological coding process is, of course, a two-way street, and what one chooses to call encoding or decoding is largely arbitrary and depends on where one enters the process. This is especially the case in the recognition mechanism. I have here chosen to call "encoding" the process that *distributes* information in the brain and to call "decoding" the process that allows *use* to be made by the organism of the information so distributed. I could as easily have chosen the more common view that encoding involves storage and decoding the readout from storage. In that case the observations reported would be arranged somewhat differently but the resulting "image" would, of course, be essentially the same.

inversely related to each other? Neurophysiology provides us with some sound clues.

Graded potential changes at synapto-dendritic junctions in nerve tissue, on the one hand, and nerve impulses, on the other, are available as two kinds of processes that could function reciprocally. The channeling of nerve impulses obviously is related to performance. Junctional neural events are therefore left as candidates to account for the orienting reaction of the organism and its habituation.

A synapse does not work by itself. Nerve impulses arrive at many synapto-dendritic junctions simultaneously. In essence, such arrivals occur in patterns that generate stationary wavefronts (5), which, once established, can interact and produce patterns similar to moiré (41) or interference effects. These effects act as immediate analogue cross-correlation devices to produce new figures from which departure patterns of nerve impulses can be initiated. The orienting reaction could well be a function of such interference effects.

Subjectively, the orienting reaction is correlated with awareness, habituation with unawareness. What evidence do we have to suggest that the graded electrical activities of the central nervous system are involved in awareness? Kamiya (24) at the University of California Medical School in San Francisco has shown, using instrumental-conditioning techniques, that people can be aware of whether their brains are producing alpha rhythms or not. Specifically, the hypothesis reads that we are indeed able subjectively to tell one pattern of junctional potential changes from another. My suggestion is, therefore, an old-fashioned one: that we experience some of the events going on in the brain, but not others. The point is an important one; if accepted, it carries with it a corollary—viz., that nerve impulse activity and thus behavior (including verbal behavior) per se are not directly and immediately available to awareness. More experiments of the kind Kamiya has performed are urgently needed.

But in order for recognition to be effected, some more permanent alteration of substrate must act to influence the configuration of arrival patterns. If one looks at EEG records coming from an EEG machine for a number of hours during the day, and then goes home to sleep, what happens? The day's records go by in review; but note—they go by *in reverse!* This is known as the "waterfall effect."

Obviously, some neural change has taken place to allow the record to be re-viewed, but also obvious is the fact that the re-viewing takes place from a vantage point different from that of the original viewing. The record must therefore have "stereo"-like properties that provide parallax and allow it to be examined now from this, now from that,

standpoint. This re-viewing from various vantage points must not lose its identity relative to the entire record: a familiar face gains, rather than loses, its familiarity and recognizable identity by being viewed from different angles.

Recently, important new advances have been made in the study of interference effects. Moiré patterns, as mentioned above, have been explored, and unexpected varieties of figures have been produced by the interaction of relatively simple grids. Even more startling in their similarity to perceptual processes are the results of a new photographic process, which produces images by way of a record called a hologram. The hologram does not visually resemble the original object—rather, it is an encoded record of the wave patterns emitted by or reflected from an object.

This process is radically different from conventional photography that records only the intensity of the image focused on the photographic plate and records detail that produces equal intensity at the film plane as equal shades of gray. Hologram photography was first used by professor Denis Gabor of Imperial College, London, in 1948, to record and then reproduce the actual wavefronts of light that issue from an illuminated object.

Professor Gabor studied the propagation of light from the viewpoint of information theory, deducing from Huygen's wave theory of light that all the information in an image must exist in every plane between the object and the photographic plate. Thus, he reasoned that it might be possible to extract the information at any arbitrary plane and then recreate an image without the necessity of using a lens.

The wave nature of light had been demonstrated more than a century earlier by Thomas Young, who showed that light waves have amplitude and phase characteristics, and that this description obeys simple laws of superposition that can be used to describe the propagation of light mathematically. From this early work, Gabor knew that both the amplitude and phase of light must be recorded. Light amplitude is only measured indirectly by the eye, film, or photodetector, the energy sensitive devices that record the square of the amplitude of the incident light. Phase information is not recorded in conventional photography.

Gabor's brilliant invention was to superimpose on the arbitrary recording plane a reference beam of light derived from the same source so the phases of light would reveal themselves by changes in intensity. The interference pattern produced by the light scattered by the object and the reference wave serves to store both the amplitude and the phase of the scattered light. In this way, Gabor produced on film a record of information in an arbitrary plane; such a record he called a hologram because it contained the "whole" information. Furthermore, when the hologram was reilluminated by the same or a similar reference beam, the light emerging from the holo-

gram emulsion formed an image of the object. Gabor realized that in this process, the wavefronts of light at original exposure time were being reconstructed.

A quasi-monochromatic light source that can be used for supplying the object illumination and coherent reference beam is required for recording and reconstructing holograms. The development of the laser in 1960 provided a convenient source of the high-energy light required and hence added an enormous stimulus to holographic research. Thus today, research in holography is being carried out by more than 100 laboratories. This research has provided a wide variety of basic techniques useful for making records with extremely high information content. (62)

These records can be thought of as a "freezing" of the information contained in the amplitude and phase relationships of wave patterns; the patterns remain frozen until such time as one chooses to reactivate the process, whereupon the waves are "read out" of the recording medium. As noted above, holograms are produced by virtue of interference effects obtained by splitting a beam of coherent light, using the major portion as a reference beam and allowing the minor portion to be reflected from the object to be photographed. A photographic recording of these effects will yield a gating-like, gridlike structure

that can be regarded as a two-dimensional analogue of the sinusoidal wave produced by an electric oscillator. The important point of this analogy is that just as an electric wave can be modulated to serve as a carrier of information . . . so can the interferometrically produced wave pattern be modulated to serve as a carrier of information about the light waves that produced it. (30)

There are many startling attributes of holograms. Among these, the following are of greatest interest to us in our search for the mechanism by which experience can be experienced.

First, the image seen by looking through the hologram is complete, three-dimensional.

As the observer changes his viewing position the perspective of the picture changes, just as if the observer were viewing the original scene. Parallax effects are evident between near and far objects in the scene: if an object in the foreground lies in front of something else, the observer can move his head and look around the obstructing object, thereby seeing the previously hidden object. . . . In short, the reconstruction has all the visual properties of the original scene and we know of no visual test one can make to distinguish the two. (30)

Second, holograms have the property that

several images can be superimposed on a single plate on successive exposures, and each image can be recovered without being affected

by other images. This is done by using a different spatial-frequency carrier for each picture. . . . The gating carriers can be of different frequencies . . . and there is still another degree of freedom, that of angle. (30)

Third, today holograms can be constructed and reconstructed (10) without the use of lasers. Further, when two or more objects are present in making the hologram, any one of them can serve as a source to reconstruct the others, which appear as "ghosts"—a simple mechanism for producing associative memory.

Finally,

each part of the hologram, no matter how small, can reproduce the entire image, thus the hologram can be broken into small fragments each of which can be used to construct a complete image. As the pieces become smaller, resolution is lost. (30)

However, as successively larger parts of the hologram are used for reconstruction, the depth of field of image decreases, i.e., focus becomes narrowed, so that an optimum size for a particular use can be ascertained. These curious properties derive from the fact that

each point on the hologram receives light from all parts of the subject and therefore contains, in an encoded form, the entire image. (30)

These properties of the hologram are just those demanded by the facts of brain physiology as they pertain to perception. One of the most puzzling experimental findings, one that led Lashley initially to propose a neurological-interference theory, is that removal of as much as 80 percent of the sensory input mechanism fails to impair pattern perception (29). This is especially odd since the anatomical arrangement within these systems is such that a topological point-to-point correspondence exists between peripheral sensory receptors and the cortex. On the basis of the evidence of relatively intact perception in the face of removal of as much as 80 to 90 percent of their volume (38), these anatomical connections cannot conceivably be assumed in the intact individual to produce ordinary isomorphic or ikonic images. On the other hand, if these essentially parallel receptor-cortical connections are conceived as constituting a neural reference beam for the construction of a holographic representation, the dilemma is resolved. For holograms have the most unusual property, as already noted, that any small part can be used for reconstruction of the entire image. Any part of the hologram contains all the information necessary to reconstruct the whole.

I have already made the suggestion that arrival patterns in the

brain constitute wavefronts that, by virtue of interference effects, can serve as instantaneous analogue cross-correlators to produce a variety of moiré-type figures. Now, by means of some recording process, a temporary storage mechanism derived from such arrival patterns and interference effects must be envisioned. Could the conformation of protein and even longer range anisotropic orderings of protein structure be altered in one direction during exposure and then later reversed, such that, as it were, "the tape plays backward"? And would this "drift" in protein memory produce a reverse drift in the synaptically produced patterns?

What is the relevance to education of a spatially encoded neural representation? Could it be that the academic community has centered too much on the teaching of skills and habits to the neglect of image? Is there something to be gained from the techniques developed by Madison Avenue? If indeed image formation is an important form of memory mechanism, should we not listen to these experts, the image makers?

Two processes dear to image makers are identification and imitation. In our recent endeavors to program learning, are we not neglecting these powerful processes for the purpose of educating? Learning through reinforcement is an important mode, and I will discuss it shortly; but learning through image-making is equally potent. A simple experiment performed in my laboratory by Dr. Patrick Bateson (4) illustrates this point. Bateson trained monkeys to discriminate between two letters of the alphabet by the usual reinforcement techniques. He then placed a third letter so as to be always in view in the home cage of the monkeys. After some months of such exposure and with the appropriate control procedures, the "home-exposed" letter and one of the previously "reinforced" letters were each paired with a new one in a standard discrimination. To our surprise, the "home-exposed" letter proved to be discriminated more rapidly. Perhaps we should not have been so surprised—my four-year-old daughter can point to and "read" the names of cereals, soaps, and other goods displayed in the supermarket. When asked how, she replies, "I learned it at home—on television." My plea is, therefore, that we not lose sight of the picturesque, for the brain is built to work with pictures.

In summary, I suggest that the perceptual mechanism is constituted in such a way that neural holograms are produced and that images can be reconstructed from the interactions of the holographic patterns. Let me now turn to this reconstruction process.

Reconstruction

The hologram is an excellent method for encoding neural events initiated by input or as the representation of patterns of neural interaction to be read out. But as a mechanism for permanent storage, the hologram accomplishes too much too soon—a plethora of memories would plague our every moment were there not some more parsimonious way to store and identify those events useful to the organism. A mechanism must exist that can extract, from the “holographic” representation, information relevant to the continuing needs and interests of the organism. This information must be stored in such a way that when subsequent input is appropriate an image can be reconstructed from the permanent remnant. How is this accomplished?

I have so far omitted from discussion the formation of a screen onto and through which inputs are projected to produce an image. The necessity for invoking such a “screen” concept comes from many sources—the simplest observation is the fact that intrinsic movement of the eyes results in a stable perception, while extrinsic movement, as by digital pressure on the eyeballs, produces a moving perception. Only by moving the screen to keep up with the projected input can the perception become stable.

To indicate some of the complexity of makeup of this screen, let me present a summary of the results of an experiment recently accomplished in my laboratory (52). Monkeys were trained to pull a lever by which a display of one of two patterns (circle, vertical stripes) was initiated. The display lasted for one millisecond and was centered on a translucent panel split down the middle. The monkeys could press either the right or the left half of the panel to close a microswitch that would initiate the delivery of a banana pellet if the correct panel had been pressed. The panel on the right was correct when the circle had been displayed; the one on the left was correct when the vertical stripes appeared.

Records were made of the electrical activity occurring in the monkey's brain (see Figure 1) while he was solving this problem. From the wave form of these records we could distinguish whether the monkey saw the circle or the vertical stripes; whether he made the correct response or an error; and whether he intended to press the right or the left half of the panel once he knew the problem. All of these differential electrical responses occurred in the visual cortex

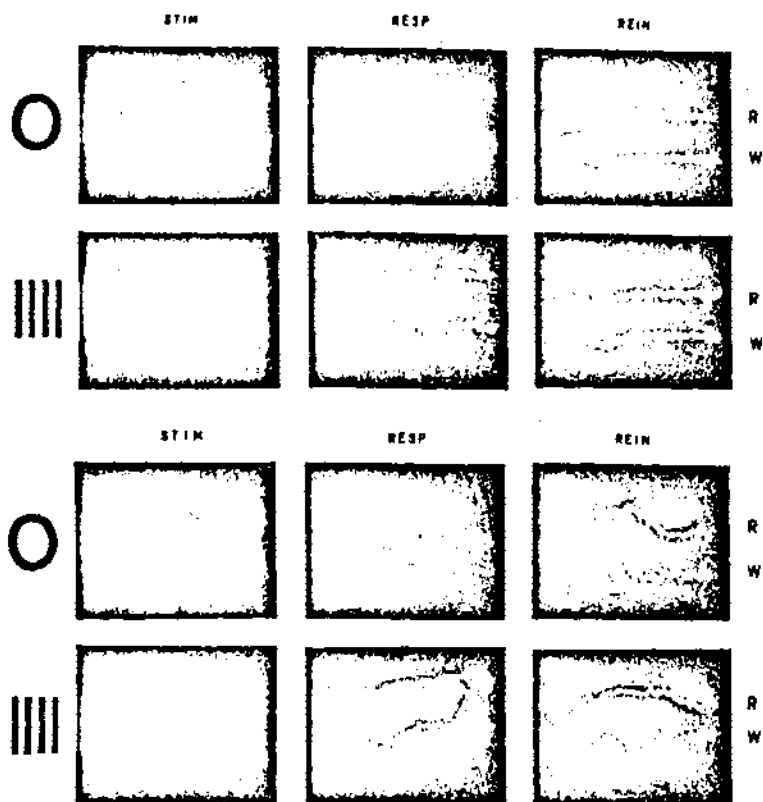


FIGURE 1 Averaged recordings of electrical activity obtained from the occipital cortex of monkeys performing a differential discrimination: circle as opposed to vertical stripes. A standard 500 msec of activity is represented in each trace; the amplitude represented is variable, however, and depends on how many more signals were obtained when the monkey made a correct response than when he made an error during criterion performance. The records under STIM are the waveforms evoked by a display lasting 1 msec; the records under RESP were generated just prior to the response; the records under REIN were generated after the response and during the period when reinforcing events occurred. The upper six panels were made from records obtained while the monkey was performing at chance; the lower six panels were made from records obtained after the monkey attained an 85 percent criterion (200 consecutive trials). The records in line with R were made when the monkey performed correctly; those in line with W were made when the monkey was wrong. The waves generated just prior to response (the intention waves) are similar whenever the monkey is about to press the right half of the panel, regardless of whether this is for the circle or vertical stripes, and regardless of whether this response proves to be correct or wrong.

(that part of the brain which also receives the visual input), though different electrodes recorded different events. Apparently, experience and current input converge in the input system.

This experiment suggests that some form of recoding takes place within the input system, making possible a longer-term storage of experience. A clue as to the nature of this recoding process comes from the theoretical analysis of Beurle (5), who has demonstrated that waveforms of the sort that constitute the neural hologram (plane waves) tend to "focus" whenever they occur in an absorptive medium (e.g., brain). The waveform is thus capable of exciting a highly localized aggregate of neurons—or even a single unit. This amounts to extracting a single dimension, a single "sinusoidal" wave and the particular information carried on it, from the multidimensional hologram. Thus the impulse configuration, the firing characteristics of a specific constellation of neurons, can be influenced by and can in turn influence the interference patterns that constitute the hologram. Unit recordings, as by Jung and his group (23), Mountcastle (35), Maturana (33), Lettvin (31), and, of course, Hubel and Wiesel (21), have amply demonstrated this specificity. From these studies it appears likely that each of the columns of cells constituting the cerebral cortex is, either innately or by experience (through the operation of the hologram), tuned to one or another specific function. Subsequent to tuning, each such column would tend to resonate—i.e., produce an identifiable output whenever the same or a similar input pattern occurred.

In my laboratory, Dr. Spinelli (57) has developed the details of a model of a memory mechanism based on these assumptions. Spinelli approaches the problems posed by the neurological evidence by focusing on the need for (1) a distribution of information in memory and (2) a simple device to decode and store the complexities of the input. Distribution of information is the major accomplishment of the neural hologram, which can realistically be derived from the operation of a Fourier transform on nerve impulses performed at synaptic junctions. Decoding is accomplished by reversing this procedure: neural units are assumed to be sensitive to two characteristics of the wave pattern, its amplitude and its phase angle. In the Spinelli model these two characteristics determine the size of the receptive field and some simple property of its configuration.

Pattern recognition has been accomplished by computer in just this fashion. By programming a device that codes amplitude and phase angle, the basic similarities of sets of complex patterns can be identified, leaving flexible a considerable range of leeway in minor

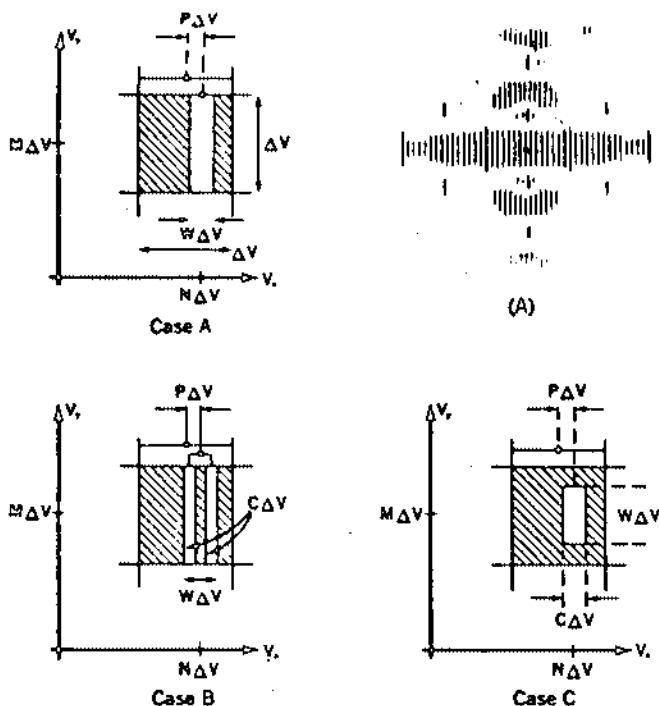


FIGURE 2 Three ways of constructing a cell from which a hologram can be reconstructed and an example of a Fraunhofer hologram that corresponds to Case A. Slit width and height, as well as the cell size, are the adjustable parameters.

differences between configurations (7). The manner of coding used in this device is shown in Figure 2 and displays remarkable similarity to the visual receptive fields of neurons in the visual system.

Long-term storage of amplitude and phase information is conceived by Spinelli to occur by timing an ensemble of units to respond more readily to those characteristics by which they have been most frequently excited. The tuning is conceived to take place by means of the mechanism of self-inhibition within the ensemble of lateral inhibition between ensembles. A diagram of the Spinelli unit is shown in Figure 3.

The characteristic essential to both the hologram and the Spinelli unit is that access to the memory mechanism is gained through a host of channels, nerve pathways, working simultaneously and in parallel. This is not to deny the importance of hierarchical organizations within the nervous system (e.g., see next section) or even within the input channels. But the fact remains, as was pointed out in the last section,

that the anatomy and function of the input systems to the brain are to a large extent organized in parallel. In this respect they differ from the commonly used serial processing computers available today.

This contrast with hardware computers provides another attribute of biological memory. Today's computers are structurally addressed—i.e., the "address" of an item is coded in terms of its location in memory. Through the hologram, information becomes distributed, and the evidence upon which the Spinelli unit is based shows that storage remains distributed. Since the hologram and its anatomical substrate provide simultaneous parallel access to all parts of the system, location of items becomes irrelevant. The chances are, therefore, that biological memory is content addressed; i.e., as already indicated, inputs with a particular characteristic will call forth (through resonance) outputs from neuronal aggregates that are tuned to the same or similar characteristics. We have all shared the common experience that a few bars or phrases of a song or a poem will start the reconstructive mechanism going and the whole will come pouring out. It may well be that Professor Penfield is providing just the right waveforms to his patients' temporal lobes to initiate such a process.

Decoding the neural holographic representation, the reconstruction of an image, is in this fashion conceived to be similar in many respects to the formation of "ghost images" in ordinary holography: the input configuration contains at least a part of the total information to be used in reconstruction.

But there is more to the reconstructive process than this. Man is not completely at the mercy of the input patterns that surround him. He can focus on this or that aspect, change what he chooses to attend to and to identify. For this operation also, a neural mechanism must exist—and indeed there is a good deal of evidence as to what it might be like.

There exist, in the primate brain, regions of cortex that, although associated with each of the input systems, operate more or less independently of the input. A good deal of my own research efforts over the past twenty years has been devoted to deciphering the functions of these associated regions. The detailed results of this research are reviewed elsewhere (42, 43), but the essential findings can be summarized as follows: contrary to popular opinion, these regions do not appear to serve as intersensory association mechanisms. Rather, there is one such area associated with each of the major sensory modes. How each area serves its sensory-specific functions remains a puzzle, but my neurobehavioral and neurophysiological results suggest that the associated areas exert their influence, via corticofugal fibers,

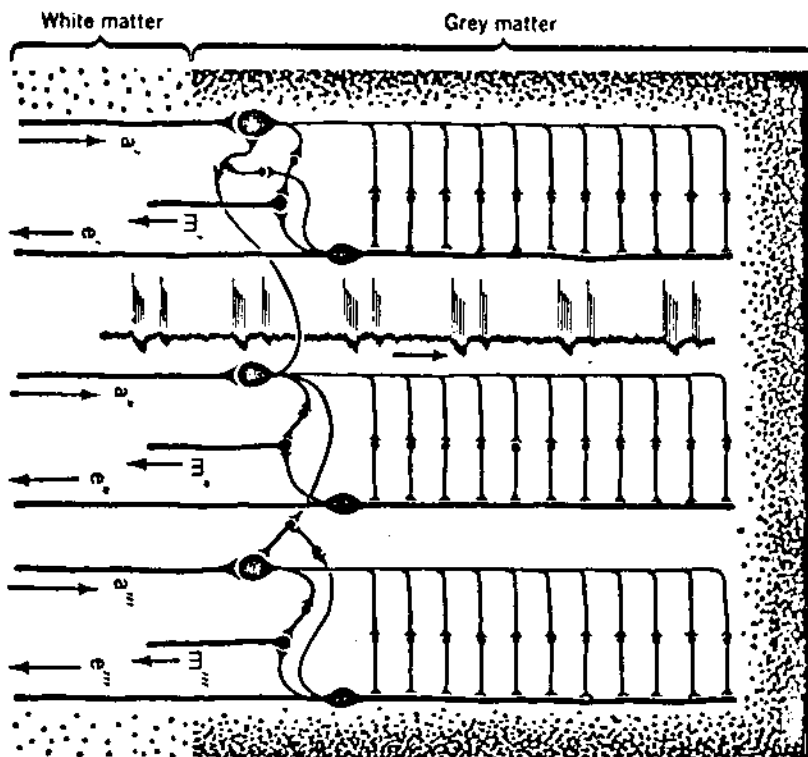


FIGURE 3 Diagram of the Spinelli unit, which operates much as does a Computer for Average Transients (C.A.T.). Thus, just as the C.A.T., it stores only the incoming activity that synchronously repeats itself. Maximum output will therefore be produced by neuron e' only when the incoming activity matches exactly the stored pattern. Neuron m' is essentially a comparator; it receives the input activity from neuron a' through an inhibitory interneuron and the activity from neuron e' through an excitatory connection. Because the assumption is that there will be an output from e' only when there is a match, an incoming signal will go through totally, in parts, or not at all, with the result that neuron m' will be disinhibited, partially inhibited, or strongly inhibited. Neuron m' will signal a match or a partial match independently from the strength of the signals; its action is essentially that of a differential amplifier or of a comparator with an integrative action over a time span of unspecified duration. In addition, the ensemble is connected by inhibitory neurons that function much as does lateral inhibition in the retina. Assuming the memory to be initially blank, this feature prevents all memory neurons from storing the same items. The amount of reduplication in the storage of one item is, therefore, inversely related to the amount of lateral inhibition. There is an added twist to the lateral inhibition: if there is an output from the middle neuron, for example, the lateral inhibition impinging on its neighbors is enhanced. The effect of this is

on the neural activities occurring within the relevant input systems. In the visual system (51, 52), for instance, the electrical activity of single neurons in the optic nerve, lateral geniculate nucleus, and cortex is altered by electrical stimulation of the visually associated area (Figure 4). In the auditory system, the corticofugal pathways involved in influencing electrical activity in the auditory system have been traced as far peripherally as the cochlear nucleus (12, 13, 37).

What is accomplished by these corticofugal fibers? Removal of the cortex of their origin impairs choice among alternatives (8, 47, 60). This impairment is due to a restriction in the sample size out of which choices are made—a restriction in the organism's field of attention. The neurophysiological explanation of this alteration of attention rests on our experiments as noted above. Specifically, stimulations and removals of the corticofugal fibers from the associated cortex were interpreted to show that redundancy could be changed by altering the number of nerve pathways used at any moment by any particular input (58, 59). Thus the *rate* of input processing can be regulated by the associated cortex.

Adjustment of the rate of information processing is thus one of the functions of the neural "screen." The inhibitory mechanisms of the Spinelli unit allow just such control to be exercised on it at the cortical level, and a somewhat similar neuronal configuration could be involved at subcortical stations (15, 48). In these locations, the screen acts more as a filter or lense than as projection surface. To return to the hologram analogy, the extent of the neural hologram at any moment is determined by these corticofugal influences. As in the

(again assuming memory to be initially blank) that when an item is presented to the whole memory, only a selected few memory neurons will become active, and each one will be surrounded by an area of inhibition. The spatial arrangement of the excited neurons and of surrounding inhibited areas is determined only by chance. Upon repeated excitation, some memory neurons will begin to output, thus enhancing the surround inhibition with the result that from then on these neurons will have a higher probability of being the foci of excitation (being "open" to that item) and of preventing memory neurons all around them from learning that item any further. From a behavioral standpoint, a learning curve should have at least two components; the first one around chance levels would be correlated with the building up of memory cells in which the activity produced by the learning situation emerges more and more from "noise"; the second, starting from above chance, should be much steeper and would be the expression of the fact that the activity produced in the memory neurons is well above "noise" and can, therefore, attract further activity of that kind to the *same* memory neurons.

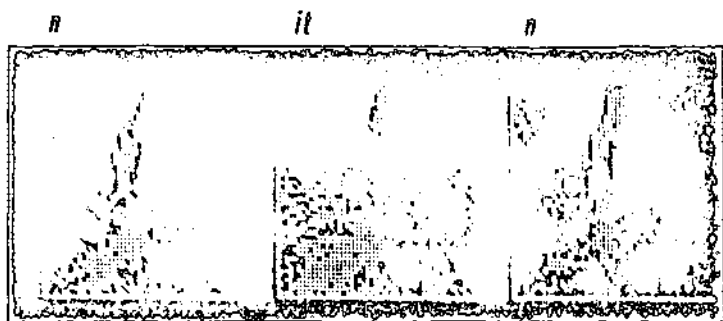


FIGURE 4 Effects of stimulation of the posterior "association" cortex of a cat on a visual receptive field recorded from a neural unit in the optic tract. These records are made by moving a spot with an X-Y plotter controlled by a small general-purpose computer (PDP-8), which also records the number of impulses emitted by the unit at every location of the spot. The record shown is a section parallel to the 2 S.D. above the background firing level of the unit. Note the dramatic change in the configuration of the receptive field, especially after stimulation of the posterior "association" cortex (IT, inferotemporal).

photographic hologram, the larger the extent, the shallower the depth of field and the greater the resolution of the parts of the image in focus (30). In other words, increasing the number of nerve pathways occupied by input at any moment increases the extent of the representative process and thus the focus of any particular aspect of the image, much as does the use of a telephoto lens. Conversely, decreasing the extent of the representative process brings into simultaneous focus a larger field (a greater number of items), much as does the use of a wide-angle lens in an ordinary camera.

The mechanism for changing the focus of attention by regulating the redundancy of the input channels was discovered by us in monkeys. However, the process appears to be a ubiquitous, primitive neurophysiological mechanism. An entirely independent series of studies on crayfish (64) has led to the demonstration in this invertebrate of a mechanism remarkably similar to the one outlined here for the primate, which attests to its biological importance.

So much for the experimental evidence obtained in the laboratory. These experiments leave unanswered the question of whether the rate of input processing is qualitatively as well as quantitatively alterable by the operation of the "associated" cortex mechanism. Here, the experiments detailed by Professor Penfield for this audience provide a partial answer. Electrical excitation of the associated cortex in man



gives rise, in the scarred brain, to sequentially ordered remembrances. This observation has been taken further in a study by Mahl (32), where implanted electrodes were used so that the stimulations could be carried out repeatedly over the course of weeks. Mahl found that the events remembered varied according to the set and setting produced by the experimenters prior to and during the electrical stimulation. An hour's conversation about childhood experiences would result in stimulation memories dating to childhood; a discussion of current marital problems would result in stimulation memories associated with the marriage. Thus, the same electrode placement and stimulus parameters could give rise to different sets of memories. The conclusion to be reached from these observations is this: the re-remembering process, in this case initiated by the electrical stimulation, must operate by assembling from their distributed locations the variety of fragments dis-membered during storage (much as a sequence-control program does for a computer). Apparently, the qualitative differences are determined by the set and setting of the moment and its immediate antecedent, not by the reconstructive process per se.

We have all made this observation. Events dimly remembered become vivid when we return to the scene of the experience. Meeting old friends, hearing familiar music, rereading in a long-neglected topic, all call forth reconstructive powers thought long since gone. We are little aware of the amount of our memory that is carried "out there"—not in our brains but in our homes, jobs, and libraries. Given these highly structured inputs, the machinery of our brains can restructure—reconstruct—a remembrance from the bits and dabs actually stored in the head. The process is somewhat similar to that familiar to us in a desk calculator—or, less familiarly, a computer. Given the appropriate input, these machines can perform herculean feats of memory: they will, for instance, repeatedly compute correctly the product of 3767×1564 and for that matter *any* combination of four

numbers. Yet none of these products is stored in the machine! The operation of multiplication is reconstructive. From the evidence I have reviewed here, it appears likely that a great deal of what we call remembering is in like manner reconstructive.

For education, the moral is clear. Instruction (shared discovery of structure) should supplement teaching (showing). The tools for structuring and restructuring must be developed by the pupil; the machinery of reconstruction must be put together. The techniques of analysis and of synthesis are to be emphasized. The simple repetition of loosely connected facts ought to give way to the search for structure in the material to which the student is exposed. The short-answer test, which explores the number of items retained (ever so briefly and meaninglessly), ought to be recognized for what it is—a labor saving, featherbedding procedure to process the students through the school system with the least possible effort on anyone's part.

As an educational experience, term papers, take-home examinations, and group test efforts produce an infinitely greater impact. How many of you still have in your files somewhere that paper you wrote in high school of which you were so proud, and still are? How many of you have had the experience of reading of a recent statement by Toynbee, or the expression of some other famous person in the news media, and exclaiming: "Why, you know, I said something like that in a paper I wrote in that history course back in 19XX"? The writing of the paper was educational, and today's reconstructive experience is possible and meaningful only because the paper was accomplished. The likelihood is slight that any one of the 500,000 short-answer questions you have had to answer during your school life has had much effect other than the deleterious one of dulling interest.

In summary, the understanding achieved by research on brain function in my laboratory suggests that the present educational effort is deficient in the techniques of image making and in the lack of emphasis on the reconstructive aspects of remembering. The real possibility exists that these deficiencies account for the fact that so many gifted individuals' schooling becomes a dull routine to be escaped as rapidly as possible. But, before the full impact of this suggestion can be explored, I must detail some of what we know about the workings of the brain in the more standard learning situation—the mechanism by which events become registered in memory.

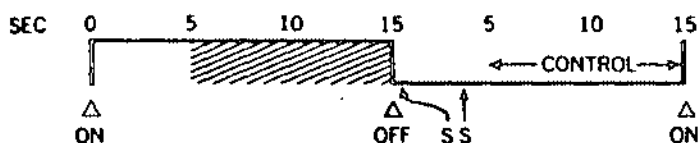
Registration: A Temporal Encoding Process

The holographic image is a spatial representation of experience in the nervous system. As such, it is momentary. Yet, as discussed in the section on reconstruction, aspects of this spatial representation become enduring. From these enduring fragments the image can be reconstructed whenever subsequent input is appropriate and sufficient to the task. The observation was also made that the reconstructive process was not just quantitative—that qualitative attributes have been identified. From this observation, it follows that there must be a brain process that functions to encode in a temporal mechanism the redundancies experienced. To begin the exploration of such a temporal encoding process, it is necessary to return to the studies on the habituation of the orienting reaction.

The work in my laboratory on this topic began (26) by repeating Sokolov's experiments and extending (3, 25) the findings to monkeys, on whom brain operations could readily be performed. These studies uncovered the unexpected finding that the orienting reaction is not all of a piece. Rather, the several measures of orienting—EEG, GSR, heart and respiratory rate, and orienting movements—were dissociated into two categories by the brain lesion (1). Further, the results of the experiments showed that the absence of one class of orienting responses was correlated with a deficiency in habituation and in classical conditioning (2). As shown in Figure 5, this deficiency is related to a failure to anticipate the consequences, the effects, of the event experienced. There appears to be a failure of normally recurring rehearsal of the conditioning events. We have therefore labeled this class of orienting responses indications of "registration." In the absence of "registration," the mapping, encoding, of experience into temporal dimension fails to occur.

The results of these experiments mirror an everyday experience shared by most of us. There are times during which we are preoccupied, when our spouses or friends rattle on, only to become aware at last that we are not attending to their words. Piqued, they exclaim: "You're not listening." We immediately try to reassure them by repeating to them the last phrase or sentence that they expressed. Our representation-reconstruction process has saved us for the moment. But, if asked some time later what the "conversation" was all about, we might well reply, "What conversation?"—with predictable results.

In man, a permanent memory defect of just the sort that is nor-



TRIALS	GRP	5-10 SEC ON	10-15 SEC ON	5-10 SEC OFF	10-15 SEC OFF
FIRST 40	NORM	3.7	7.0**	3.9	7.0
	AMX	3.2	3.3	3.9	6.3
SECOND 40	NORM	5.7**	8.8*	6.2	4.5
	AMX	2.7	4.8	3.5	4.3
ALL 80	NORM	9.3	14.5*	10.3	7.0
	AMX	5.8	8.2	7.3	6.3

* = $p < .08$

** = $p < .05$

MEAN NO. GSRS IN PERIODS PRECEDING SHOCK
(ANTICIPATORY RESPONSES)

FIGURE 5 The top of the figure shows a conditioning paradigm in which a light is turned on, then turned off after 15 sec. Following this by 3 sec is the onset of shock. The table shows the number of anticipatory responses made during the first and second forty trials, which show in the shaded area of the diagram above. Note that normal S's make more and more anticipatory responses and that these occur earlier and earlier. Note also that monkeys who have been amygdalectomized show no such anticipatory response.

mally shown during periods of preoccupation has been related to lesions of the same parts of the brain ablated in our monkey orienting-reaction experiments—the medial portions of the temporal lobes, which include the limbic structures amygdala and hippocampus. Such patients have been studied extensively (55, 61) with behavioral techniques, as have monkeys with similar lesions (11, 40). Detailed reviews of this work are available (14, 16), and this is not the occasion for analyzing the complexities of the results. This general statement may be made, however: all of these studies show that these parts of the brain become important in situations that demand of the organism an active organizing process entailing rehearsal and relation in some new fashion of his past experience to the current circumstance. The process can be conceived to encode and distribute redundancy in a temporal mechanism much as the neural hologram achieves the distribution of redundancy spatially. When this active organizing process is engaged, events are promptly registered in memory. Without the operation of this mechanism, items must be repetitiously presented to the organism before they become "memorized."

I have elsewhere (45) presented evidence for the suggestion that this organizing process is what takes place in behavioral experiments

when an organism is reinforced. The involvement of these limbic temporal-lobe structures in reinforcement is well documented (39, 54). However, before proceeding further with the analysis of the temporal-lobe contribution to reinforcement, let me turn to the neuronal level for a suggestion as to the direction inquiry into the mechanism of this organizing process might take.

The suggestion is that the reinforcing process accomplishes in the nervous system what the mechanism of induction achieves in the embryo (17, 18). The superficial descriptive similarity between induction as studied in embryological tissue and reinforcement as studied in conditioning situations has been presented in another manuscript (46) and is reviewed briefly here:

(a) Inductors evoke and organize the genetic potential of the organism. Reinforcers evoke and organize the behavioral capacities of organisms. (b) Inductors are relatively specific as to the character they evoke but are generally non-specific relative to individuals and tissues. Reinforcers are relatively specific in the behaviors they condition but are generally nonspecific relative to individuals and tasks. (c) Inductors determine the broad outlines of the induced character; details are specified by the action of the substrate. Reinforcers determine the solution of the problem set; details of the behavioral repertoire used to achieve the solution are idiosyncratic to the organism. (d) Inductors do not just trigger development; they are more than just evanescent stimuli. Reinforcers do not just trigger behavior; they are a special class of stimuli. (e) Inductors must be in contact with their substrate in order to be effective. Contiguity is a demonstrated requirement for reinforcement to take place. (f) Mere contact, though necessary, is insufficient to produce an inductive effect; the induced tissue must be ready, must be competent to react. Mere contiguity, though necessary, is insufficient to produce reinforcement; shaping, deprivation, readiness, context, expectation, attention, hypothesis—these are only some of the terms used to describe the factors which comprise the competence of the organism and without which reinforcement cannot become effective. (b) Induction usually proceeds by a two-way interaction—by way of a chemical conversation (6). Reinforcement is most effective in the operant situation where the consequences of the organism's own actions are utilized as the guides to its subsequent behavior.

A good deal of experimentation and speculation has been aimed at this problem. Much of it, unfortunately, has been concerned not with reinforcement but with inhibition. But this is not too different from the emphasis in experimental embryology, which has been almost totally concerned with the problem of segregation.

In short, embryogenesis is dependent not only on the inherited and inherent properties of the genetic constitution of the organism; rather,

these properties are evoked and organized by the inductive capacity of the milieu in which the cells grow. The inductive capacity is itself specific, but in a somewhat different sense than is the genetic potential. The *genetic capability* is individual-, species- (and genus- and order-) specific. Hereditary factors prescribe commonalities with the past and future, while assuring variation within any single generation. *Inductors*, on the other hand, are nonspecific with respect to individuals, species, and so forth. They are relatively simple chemicals—RNA's—common to all living organisms (36). Inductors thus provide the existential commonality that allows the possibility of modification of whole generations according to the exigencies of the time.

But when this much has been said, the question still remains: do these descriptive similarities point to homologous mechanisms? My hypothesis states that they do. What evidence is there in support? What neural processes become operative during learning?

The story of the experimental findings in the embryological field is paralleled by results in the field of learning experiments. You have been given an extensive review of this story by Professor Hydén. His view, based on the beautiful series of experiments accomplished in his laboratories, holds that RNA "induces" the derepression of genomes in central neural tissue just as RNA induces the formation of structures in embryonic tissue. The nature of the neural "structures" induced remains to be clarified; but I have elsewhere (49) suggested that, among other possibilities, actual neuronal growth may take place. This growth could readily be guided, in the central as it is in the peripheral nervous system, by surrounding glia. According to this hypothesis, secretion of RNA from a repetitively stimulated neuron induces surrounding glia to divide and open a pathway for the neuron's growth cone.

If we return now to the temporal-lobe mechanism, it is clear that any induction-like process needs time to take place. I have already noted that segregation is important to the occurrence of embryological induction. In the nervous system, inhibition has a somewhat similar function. It has been well established (19), both for the retina and for the cerebral cortex, that an externally derived excitation at any locus will produce inhibition in the surrounding tissue—i.e., the frequency of spontaneously occurring electrical discharges of the inhibited cells will diminish. This "surround" or "lateral" inhibition will tend to isolate the focus of excitation and enhance the contrast between stimulated and nonstimulated regions. Such isolation is necessary for differentiation to be accomplished neurally and behaviorally

as well as embryologically. In addition to lateral inhibition, other inhibitory processes are known to occur (e.g., recurrent or Renshaw inhibition). These act as mechanisms of self-inhibition, "segregating" one neural occurrence from another in time, much as the lateral inhibition mechanism accomplishes spatial segregation. There is, in fact, good evidence that the limbic structures of the temporal lobe have a great deal of influence on these inhibitory mechanisms (9, 20, 48). Further, neurobehavioral studies, taken in conjunction with the physiological studies already presented, have made it likely that the orienting reaction is a function of lateral inhibition, while habituation is a function of the longer lasting self-inhibitory process (15). We have thus come full circle: the organizing process of registration, which we call reinforcement, is made possible by the "segregation" of neural events through the operation of the mechanisms of the orienting reaction and its habituation.

This is borne out in fact by studies, extensively reviewed by Magoun for this series, in which direct electrical intervention in the nervous system was shown capable of guiding and modulating behavior. Electrical stimulation with alternating or pulsed currents, or polarization with direct currents, speeds or slows learning according to the parameters of stimulation used. Especially effective guides to behavior are brain excitations that the organism itself can produce in the temporal lobe and related structures. Such self-stimulations are, if anything, more potent than extrinsic reinforcers.

In summary, registration is thought to involve two related processes. One is control over afferent neural inhibition (see Figure 6), in the form of an orienting reaction and its habituation, which allows the spatial and temporal segregation of an event. The other is a reinforcement mechanism, which guides the development of the neural structures that in turn program behavior. Orientation and habituation are believed to minimize interference among events, allowing time for a process similar to rehearsal of an experience to take place. As a result, an RNA-induced reinforcement mechanism could become operative to encode successive patterns of events in the brain, either as actual neuronal growth, or by some alteration in membrane properties, or both. Such a course of events is but one route, albeit a plausible one, by which experience can become registered and capable of subsequent influence on the psychological process. As data accumulate, other routes will undoubtedly be suggested.

The relevance of the registration mechanism to education may be discerned in the effect on learning of medial temporal-lobe lesions in

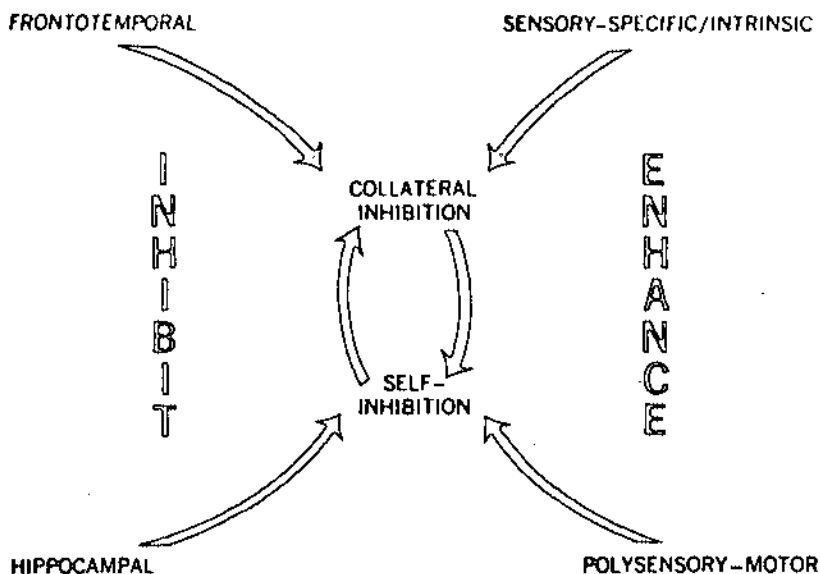


FIGURE 6 A model of corticofugal control over input processing. Collateral inhibition is considered the basic process for the orienting reaction; self-inhibition is the basic process for habituation. Two corticofugal systems enhance and two inhibit this basic mechanism of afferent neural inhibition. For details see text and (15).

monkeys. These monkeys can still learn: provided the experimental conditions are repeated over and over, the task is mastered, and, once mastered, it is not forgotten. But the learning is slowed.

Similarly, we can drill our students to attain never-to-be-forgotten skills. My father quoted the first chapter of Caesar's *Gaul* to me in Latin without error decades after he had first memorized the words. He had been exposed to 14 grueling years of Latin. I decided after this episode that for me even 2 years was too much—and the academic community has since supported my decision. How much of what we now teach our youngsters looks to them as Latin did to me? How often do we ask of them that they learn by rote what they might better achieve by engaging their registration mechanism?

Only this morning I read a Berlitz advertisement in the newspaper. "Learn any language by total immersion in 10 days" the blurb proclaimed. I tend to believe in the efficacy of their method—the registration process is sure to be taxed by any such procedure. Perhaps the learning is incomplete, and perhaps it is not altogether permanent—but then how much do you remember of your 10 (or 100) weeks of high-school French?

I give these examples not to indicate that one or another method of instruction is better or worse than another. For some purposes memorization is ideal, as when an aspiring physician must quickly master drug dosages. Rather, my question is: "Can the material presented to our students be made relevant to their aspirations and values?" Once this is done, we can "immerse" them in the material and let them proceed in their own way and at their own speed. The advent of programmed instruction has given this approach new feasibilities where repetition and practice are necessary, as in the development of skills. However, even in the past, once engaged, the student found his way to those stacks of condensed programs—the libraries.

Thus, teachers will never be superfluous. Responsible and enthusiastic educators serve as models for identification and imitation as already noted. And instructors must help decode and recode the flux of material as it is registered, or else the registration process becomes quickly overburdened and grinds to a halt. It is to the teacher that the burden of relevancy falls.

Rearrangement

Decoding the temporal structure of redundancy poses as complex a problem as does the encoding of it. Take this essay for instance. It is made up of multiple rearrangements of almost infinite repetitions of only twenty-six characters, the alphabet. How do we proceed to decode this stream of symbols?

McCulloch has provided us with a clue in a by-now famous illustration of the problem. He presents the following puzzle for deciphering:

INMUDEELSARE
INCLAYNONEARE
INPINETARIS
INOAKNONEIS

How much time it takes to make sense of this conglomeration of letters. But how easy it becomes when written or spoken as:

IN MUD EELS ARE
IN CLAY NONE ARE
IN PINE TAR IS
IN OAK NONE IS

In a similar vein, Miller (34) has pointed out that what constitutes an item or event in a biological information-processing system varies according to how the information is "chunked."

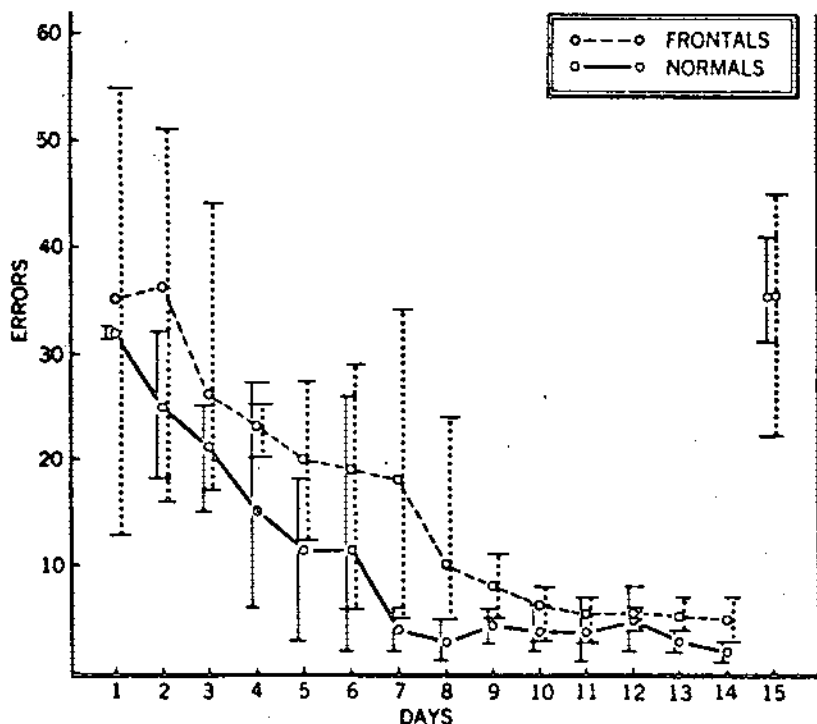


FIGURE 7 Graph of the average number of errors made by monkeys having ablations of the frontal cortex and by their controls. Bars indicate ranges of errors made. For day 15, records are shown of the number of errors made on return to the classical 5-sec alternation task.

As a first step therefore, it appears that decoding temporal structure involves a proper division, a partitioning—parsing—process. I put this idea to test in a simple experiment. In monkeys, a very specific difficulty in problem solving occurs after ablation of the anterior frontal cortex—an operation similar to the once popular lobotomy procedure performed as psychosurgery in man. This difficulty is manifest as an inability to perform a variety of sequential tasks, the simplest of which is a right-left alternation (22, 51). The precise nature of the difficulty has resisted clarification despite much effort (50). In view of the importance of parsing and chunking in decoding verbal material, I ventured to parse artificially the alternation task for frontally ablated monkeys by inserting a 15-second pause between each right-left couplet. Thus, the task that was right-left-right-left, etc., was parsed to read right-left, pause, right-left, pause, etc. As can be seen in Figure 7, the monkeys immediately began to solve the problem.

The conclusion to be reached from this experiment is that ordinarily the anterior frontal cortex supplies a mechanism that decodes the flow of events by inserting "pauses" at the appropriate time, thus providing a grammar, as it were, for the psychological process and behavior (53).

On the basis of the results of other neurobehavioral experiments, I ventured a few years ago to suggest that the anterior frontal cortex functions much as does a "flexible noticing order" in a computer program (50). In the computer, such a device acts as an executive, giving priority now to this, now to that, set of events being processed by the computer. Since the time this suggestion was made, computer science has progressed considerably. Executive routines based on "flexible noticing orders" have become important tools for allowing time sharing—i.e., the use of a single computer by a number of users. Time sharing is a decoding operation: items must be sorted and separated according to the user, despite the fact that both the input and the events in the computer become temporally intermixed.

We have met a similar problem in the discussion of reconstructive remembering. There the issue was to reassemble items distributed spatially in the nervous system; here the task is to arrange in some order items distributed temporally. As in the case of the reconstructive process, a great deal depends on the appropriate structure—or structuring—of the input. This is clearly indicated by the jumble resulting from unparsed verbal material even in us, who presumably possess creation's finest executive organ, the human frontal lobe.

What do we know about the neurophysiological operation of the temporal decoding mechanism? As already noted, electrophysiological experiments have shown that input processing can be slowed by electrical stimulation of the frontal cortex. This slowing results from an increase in effective redundancy within the input channel, which also has the effect of reducing interference among the events being processed. In this respect frontal-lobe function is similar to that of the medial temporal structures.

But, aside from these initial findings, practically nothing is yet known. There is some hope that new insights will come from the recently discovered Contingent Negative Variation, a slow potential change that originates somewhere in the front of the brain whenever the organism is preparing to respond (28, 63). This and our finding of a wave preceding meaningful response in the input systems (already noted) provide indicators of intentionality and so allow exploration of the mechanism of temporal decoding. After all, a great deal is already accomplished when we know where to look and have some tools with which to do the looking.

These experimental results suggest that a great part of the educational process, except for the acquisition of skills, lies in arranging and rearranging one's experiences. When I was in college, as today, there were individuals who "cribbed" during exams. One of the most effective methods was to condense the most important material onto small cards or even onto the inside of the shirt cuff. I was impressed and envious—identification and imitation quickly suggested itself. But as I began to work studiously through the course material in order to compress the relevant facts and ideas adequately, I found that I could go the "cribbers" one better. The arranging and rearranging of notes constituted a superb review. And the aim toward parsimony in expression left me with a few key cards, which could now easily be committed to memory, since a context had been provided by the review. With one stroke, rearrangement had given me superiority: not only did I remember the material for the examination; I gained knowledge of enduring value and didn't have to risk disruption of my social fabric or of my conscience.

According to this view, lecturers should present but few facts that are to be remembered, unless these are unobtainable elsewhere (in which case precise note-taking is to be encouraged or handouts given ahead of time). Rather, a lecturer should arrange and even rearrange material that the student can, with informed guidance, find for himself. Each set of lectures should provide a framework, a core idea on and around which the student can build for the remainder of his life. Further, the student must be prompted by his instructors to make his own rearrangements. He can do this in term papers and in research endeavors, and he will, of course, use his instructor's lectures as models. If these are sufficiently flexible in approach, the student's work will reflect this. These are some of the lessons to be learned from the study of how the brain functions in remembering, although they may seem fairly tame to those involved daily in the educational process.

I have had nothing to say (although some things are known—e.g., 44) about such important topics as transfer, which allows knowledge gained in one situation to be applied in another. Nor have I discussed (because there is as yet so little to discuss) symbol manipulation, a process basic to most human educational effort. And, when it comes to creativity and originality, the neuropsychologist today has nothing solid to offer. But I am far from discouraged by these deficiencies. Only a little over a decade ago Lashley had to admit that, according to the neurophysiological and neurobehavioral facts then available, learning and remembering were simply impossible. What a difference

today, when we can look at the details of the spatial and temporal coding mechanisms reviewed here, the possibility of analysis into encoding and decoding processes, the richness of data and of analogous and relevant hardware from which we can derive precise and testable hypotheses. No, I am encouraged that indeed we are finding man's brain to work as it must, to produce the behavior we encounter. We often observe that man's destiny is in the hands of its educational process. But the currency of education is based on brains. When we knew little of brain function except that it controlled the body's economy, we were apt to pit man's baser nature against his ennobling culture or play the reverse theme of the noble savage and degrading civilization. The scientific as well as the humanistic literature is full of unfounded allusion to the primitive, the older neurological processes that have become overlaid with the mechanisms that distinguish man from beast. There is, of course, some truth in these assertions. However, the mammalian visual apparatus is as hoary as is the apparatus that regulates hunger and sex, and the truth is that the neural formations and psychological processes that regulate appetite in man have developed easily as much as have his mechanisms of vision. There are no subhuman gourmets, nor have the beasts as yet produced a Marquis de Sade—they just don't have the brains.

The simple fact is that our view of the world depends in large part on our view of ourselves. And the organ crucially involved in viewing is, of course, the brain. Better we know it well, how it represents the world and reconstructs its images. Better also that we know well the tricks that can be played on us by our memories—how registration can occur and how it can fail. And we must come to know the limits of resolving power when our brains are faced with temporally organized codes.

These then are the frontiers of mind: developments in neurobehavioral science that permit man to evolve his understanding of man.

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