T-149

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BRAIN AS THE MEDIUM FOR THE SCIENCES OF MIND

Introduction

All my life I have been intrigued by the mystery of mind and especially by the bodily machinery that makes mind possible. As a college and medical student I was therefore naturally drawn to the disciplines concerned with the nervous system, which together with the endocrine, serves as the great integrator of bodily functions. I was not made aware of the possibility that mind could be studied scientifically, but the faith abounded that a thorough knowledge of physiology in all its ramifications would come up with the answers I sought.

This faith was not to be disappointed. As is so often the case, however, nature did not and does not yield her treasures in any straightforward fashion. Scientific inquiry had to devise many strategies to divest mind of her modesty. On the other hand, once her privacy was breached no one could be sure who had done the breaching, though many appear today to be beneficiaries in one way or another of her favors. Thus, a constellation of disciplines is now devoted to solving problems which, not so long ago, were felt to be beyond the pale of hard-headed research. These disciplines pursue their goal under a variety of banners, but they share common interests and borrow heavily from one another not only ideas but techniques and data as well. In academe this ferment is felt in a variety of ways. Psychology which perhaps had the best initial strategy in tackling mind by way of experimental analyses of behavior became so engrossed in its technology that the opportunity was at least for a long time lost sight of. In the past decades, however, psychology has to some extent reassessed its purpose and returned to the broader issues of mind. This development is directly traceable to the advent of the computer sciences which have made possible the precise programming of information processes, i.e. of cognitive functions.

Biology also has felt the impact of the newly possible. Here, the measurement of behavior as a variable has opened windows to new horizons. Psychobiology, biological psychiatry, biobehavioral sciences, and psychopharmacology are some of the labels borne by mind scientists in schools of biology and medicine.

The engineering faculty has not been spared from the new developments. Computer and simulation scientists, robotologists, biomedical and system engineers are only some of those making direct contributions to the problems of mind. News in the field of optical information processing, or in artificial memory construction, is news that quickly spreads beyond the institutes of technology to the entire community of scientists of mind.

At the core of all of this activity stands the brain scientist, the neurobiologist, neurochemist, neurophysiologist and neuropsychologist who is presently to be found in as various locations as is the money that supports him. Even here, however, recognition of growth is becoming manifest. Neurological and brain research institutes, departments of neurobiology and neurological sciences are more and more coming into evidence.

To give some feel for the content of this research on mind I will turn to my own work because I know it best and because it covers a fair range of the problems currently engaged by my contemporaries. But, I need to point out that not all of my contemporaries necessarily share my interpretations of the available data. Some of my friends and colleagues have even aired despairing views to the effect that sciences of the mind are not possible at all (e.g. Sigmund Kock in the September 1969 issue of *Psychology Today* or Arthur Koestler's *The Ghost in the Machine*). They feel that they have learned little from the myriads of individual experiments performed in the behavioral mode of investigation. They bemoan the fact that we cannot, on the basis of these experiments, prescribe better for our educational system. My answer to these colleagues is that they have been asleep and are now lazy. As I will here indicate we now know a great deal which we did not know a quarter of a century ago. One must ask the right questions, however, if one is to obtain answers. Also one must be modest in one's demands. Research is long, hard labor. It took decades and much engineering know-how to provide direct evidence that anything is going on in the brain during an experience. Personally I was thrilled when two of my colleagues accomplished the first of such experiments only a few years ago. Since then a good deal more has been done. Yet one could, despite these data, even today, easily and loudly go about declaring that we know practically nothing about how the brain codes experience. Instead, some, including those in my laboratory, became sufficiently excited by the possibilities these experiments presaged to have initiated a series of studies to follow through on this pioneering effort. But this follow-through did not come easily or rapidly; a full *seven years* of effort were needed before the first experimental result could be reported. My faith is that the scientific process will sooner or later convince either the despairing or me of the error in our ways. In the meanwhile the excitement of the search and the rewards already harvested, belie for me any pessimistic view of the matter.

Minding Mind

Let me begin, therefore, with an attempt to spell out the premises that I believe to underlie the study of mind. Though few in number they must be able to account for the variety of actualizations in the catalogue of disciplines already noted. My first premise therefore derives from this need for variety. I believe that the reason for variety is that mind is in the first instance a private affair. But this privacy need be no greater deterrent to scientific inquiry than is that other privacy of the atom. Every child begins the process of opening his mental life to consensual validation. The scientist simply carries this process further and makes explicit the rules for validation. One of the impressive contributions of computer science has been the ease with which these rules can be made explicit and tested for internal consistency.

My second premise is that brain is the organ of mind. I do not exclude the remainder of the biological organism nor its transactions with an environment from making contributions to mind. Chemical determinants of mood, experiential determinants of learning and remembering for instance, are to be considered as a matter of course. But all of these other determinants exert their effects by way of brain. Without brain there is no mind.

Third, I define mind in terms of language derived from social discourse about the subjective world. Objectivity about mind must therefore be arrived at through inference from data described in some other language. Thus mental concepts are inferred from behavioral or neurological observations to the extent that these fit subjective experience. There can be and are a large number of behavioral and neurological data which are at the moment irrelevant to problems of mind.

These premises, and even the whole idea of the study of mind, may still strike some as fanciful. In part this may be due to misconceptions of what is encompassed by the term mind. If instead of mind I say consciousness, or instead of consciousness, perception, or instead of perception, vision, or better yet visual pattern recognition, the problem gradually comes into focus. Few would argue with the statement that the dimensions of mind called vision and recognition can be studied with today's techniques. The procedure, as in any other science, lies in taking small bites of the problem area for investigation at any one time. The vast territory which called for exploration is thus gradually cultivated.

Remembering

One of the most dramatic advances that have occured during the past decades devolves on memory functions. The initial impetus was given by the discovery that when a neuron is electrically excited it secretes large amounts of RNA. Shortly, it became clear that the glia surrounding the neuron formed a metabolic couplet with it and that the RNA played a vital role in glial-neural metabolism.

Scientists were intrigued and suggested that experiential memory worked much as does genetic memory — that bits of information were encoded on macromolecules by virtue of selective depression of DNA regulated by the amount of local neural activity. Much work has gone into testing this thesis (at one point, a few years ago, twenty groups of investigators were pursuing this topic on various campuses of the University of California alone) and it continues to be an active focus for inquiry in the sciences of mind.

At the same time, the fact that glial-neural metabolism is accelerated by neuron excitation renewed the century-old search for neural growth generated by experience. I suggested for instance, that the RNA secreted by nerve excitation could act as an inducer (much as an inducer works in ontogenesis) on the surrounding glia causing cell division. Ordinarily the growth cones of neurofibrils are capped by glia. Should the glia divide, the growth cone can poke in between the daughter glia to extend beyond and make new contacts. This course of events takes place in the peripheral nervous system during nerve regenerations: Schwann cells, the glia of peripheral nerves, perform in just this manner. My suggestion was therefore that in the central nervous system also, glially guided neural growth would occur as a result of excitation produced by experience. The results of several studies have tended to support such a thesis. Rosenzweig, Diamond and their colleagues at the University of California at Berkeley have shown that local thickening of the cortex of rats occurs in sensory enriched environments; the thickening is due to glial and nerve fiber proliferation; it is limited to the part of the brain enriched by the experience. Conversely Riesen and his coworkers at the University of California at Riverside have demonstrated that sensory deprivation results in defective growth, especially of dendritic arborizations, again limited to the part of the nervous system subjected to the deprivation.

While the research on chemical storage and neural growth has continued, another important avenue of investigation has opened. It is a truism that memory loss due to brain damage is not restricted to loss of any specific memory trace. Local brain damage results in the way, the avenues, the processes by which something may or may not be remembered. This fact has given rise to the inference that memories are stored in a distributed fashion, that they become dis-membered before being re-membered. The nature of distributed stores remained a complete mystery until the invention of holography. The holographic process converts ordinary images into a distributed representation. The mathematical description of this transformation is called a spread function — i.e. each point on the input becomes « spread » or distributed over whatever extent of film is available. Since this spread is accomplished for every point on the image, each section of the hologram incorporates all points: the image becomes enfolded onto the hologram, the whole image becomes enfolded into every section.

Research over the past 15 years has shown that such an enfolding process takes place between the sensory surfaces of the body and the cerebral cortex. Each cortical cell enfolds within its receptive field that part of the sensory image which the connections with the sensory surface make available to the cortical cell. The arrangement of these connections is such that the arrangement of cells on the sensory surface with regard to one another is maintained more or less intact, thus the sensory and motor « homunculi » found in cortex which represent the sensory surface. But it is within the receptive field of each cortical cell that the enfolding has taken place as a function of inhibitory connections with its neighbors.

Each nerve cell in the brain is composed of a body and extensions which reach out from the body to make connections with other brain cells. For many brain cells, though by no means all, one of these extensions, usually bigger than the others, relays signals to other cells. The other extensions of the cell do not relay signals. Instead they intertwine with extensions from other cells, receive signals and alter them by way of allowing interactions to occur among them. The relay signals are on/off in nature; the interactions among signals within the networks of extensions are more like wavelets which make up fronts which can interfere or reinforce at their intersections. The patterns produced in these receptive fields of brain cells are the neural equivalent of holograms. Recordings made from single cells in the brain cortex have shown that the patterns in their receptive fields are characterized by the same sorts of spread functions as those which caracterize holograms.

Holograms have all of the remarkable properties of brain. Cutting them into pieces does not destroy their power to recreate images since the necessary information is distributed over the entirety of the film. Associative recall is produced by an input describing one of a pair of previously related items — the other appears as a ghost image. Recognition, i.e. image construction, is practically instantaneous since the entire surface of the film is addressed simultaneously. And storage capacity is fantastic because by means of simply changing the position or some other attribute of the input slightly, the interference patterns produced change and therefore for every position a uniquely retrievable pattern is available. IBM has already utilized holography to create a centimeter cube which contains 100 billion bits of retrievable information and uses such holographic processes to automatically scan grocery store packages which in the United States are identified by patches of stripes of various widths and spacings. The identification is relayed to a computer which prices the item for the clerk and records the transaction for inventory control, etc.

Attending

So much for how storage may occur. A good deal has also been learned about what is capable of being remembered. If remembering consists of the reconstruction of images and the like from some dismembered, distributed store, how does it come about that we can remember some things and not all; how is it that we can remember at the appropriate time and place? Some of the appropriateness is determined by the input, especially during recognition. But what of recall, where the input configuration rarely and only remotely resembles what is to be recalled?

In holography, the position, the reference or set, from which the recording is made is critical to subsequent retrieval. By reinstituting this set, recall of the initially stored information becomes possible. I have interpreted the results of a series of experiments performed in my laboratories to show that a similar « setting » mechanism is present in the brain.

These experiments deal with the functions of those portions of primate cortex usually referred to as association areas. Our work has called into question the assumed associative functions of this cortex. What we have found is that the various areas function specifically in one or another sensory mode and that this specificity comes not from input to the area but from the fact that its output regulates the functions of one or another sensory projection system. This finding is part of a large number which have changed our views of the organization of the central nervous system. Not so long ago the conception was that the sense organs operated upon, and motor mechanisms were operated upon, by the nervous system much as a piano player operates a piano. We now know that this is not the case. Instead of a piano, the model has become the thermostat. Feedback and feedforward loops characterize the system. If I want to turn on the furnace I do not go and depress a switch. Instead I change a setting on the device which regulates the turning-on and turning-off of that switch. There is every indication that the cortex associated with the primary projection systems operates in this manner. The pathways from this cortex extend downstream into « motor » structures which in turn control the receptor structures and the afferent pathways from them.

Further, electrophysiological experiments have shown that these controls are identical with the ones we use when we attend. Electrical stimulation of the temporal lobe area associated with the visual system is ineffective if a monkey is already attending visual objects; when he is not doing so, such stimulation produces changes in potentials recorded from the visual cortex identical to those obtained when the monkey is attentive.

These experiments and others showing similar effects suggest that remembering is in part at least dependent on what is attended. This conclusion is reached on the basis of the fact that learning and remembering of choices based on prior experience is greatly impaired when the so-called association areas are resected. We have also investigated the precise relationship between attending and choosing by continuously recording the observing behavior of our subjects with an eye camera which makes a movie of the scenes reflected in the cornea of the eye ball when such scenes are in the line of sight of the observing, attending individual. Changes in the frequency and duration of visual attending are readily picked up in this fashion so that a reasonably objective measure from which this elusive mental activity can be inferred is at last obtainable.

As always when objectivity is finally achieved, the story turns out to be considerably more complicated than it was initially conceived to be. What we found was that when the eyes lingered or returned to a scene, this indicated that the monkey was interested or was having difficulty; that when the eyes rapidly scanned the scene, the monkey was processing automatically, without difficulty, correctly choosing among alternatives on the basis of reinforcing contingencies. There is no hesitation in the normal course of attending: the scene appears to be taken in at a glance. Apparently, selective attention operates within an ambient gaze which rapidly processes successive inputs to the senses.

In addition to the selective functions of attention which aid remembering by changing ambient settings in the brain, another mechanism of attention has been shown to exist. Opposing selectivity is a function which concentrates and focusses attention. The two processes, selection and focussing, are related by a mechanism which operates much like a zoom lens to enlarge the field of attention or conversely to concentrate it. Paradoxically, the parts of the brain involved in enlarging the attentive field, enhancing ambience, are also the ones involved in selectivity. Focussing appears to be related not to selection but to maintenance of vigilance in the face of familiarity and novelty.

Knowing, Thinking and Emoting

The dimension « familiarity-novelty » has cropped up repeatedly in psychological research over the past decade. First, it was established that the brain continuously builds a representation of experience and that every subsequent experience is matched against that representation. Thus, repetitions of events that are expected become familiar and the unexpected is reacted to as novel. Physiological measures of this reaction include such visceral manifestations as the galvanic skin response and changes in heart and respiratory rate as well as some changes in electrical brain rhythms. The totality of the reaction to novelty is called the orienting response. Characteristically orienting habituates upon several repetitions of the initial event.

We have found resections of the frontal cortex and parts of the limbic forebrain abolish the visceral components of orienting while leaving behavioral orienting intact. Concomitant with the interference in visceral responsiveness, however, comes a marked retardation of behavioral habituation. We reasoned therefore that the orienting reaction is made up of two components, one indicating the scanning of the novel cue, the other its registration in awareness and memory. Registration is signalled by the visceral components of the reaction.

Interestingly, these same visceral indicators have been used to study emotion. In this context they are labelled evidence for the occurrence of behavioral arousal or neural activation. At least one other investigator (Berlyne of the University of Toronto) has noted these divergent interpretations of similar results and tried to make some sense of them. The simplest way to think about the data is to state that arousal is necessary for registration. More can be said, however. It is novelty that leads to the complex of orienting reactions and novelty can be measured precisely in terms of information theoretic conceptions. Novelty is a change in repetitious events, a change from the expected, the familiar. Experiments performed by Swets in the Netherlands have shown that the galvanic skin response associated with arousal varies as a function of such changes in patterns of repetition and not the amount of information which characterizes pattern. Thus we meet once more the balance between selective attention which operates on ambient information and focussed attention which deals with novelties within the background of the familiar.

Programming the Brain

How can contextual changes come about? This question returns us to the initial one asked in this paper: how is the familiar organized in memory, i.e. in the brain? The answer given earlier on was that memory is distributed and that remembering is a reconstructive process. This answer is obviously insufficient to the present purpose which demands that some sort of context, some skeleton, be provided within which reconstruction can take place.

The problem is not much different from that faced by those working with computers. Events are stored in computer memories in a variety of ways but storage is never isomorphic with the task in hand. A program must be constructed to address the memory, and organize relevant items to the immediate purpose. How then are such programs composed by computer scientists? Fitting a computer to play a game of chess gives a good account of how it is done. The set of rules of the game is given to the computer and also a series of initial moves. The computer is then matched against a human opponent. If the computer loses (which it always does initially) the opponent is asked to introspect the rule or move that allowed him to win. This introspected datum is then programmed into the computer for the next round of plays. Gradually in this fashion computers have become chess experts able to take on any but the best of opponents.

At dinner one evening with Kenneth Colby of Stanford and Alan Newal of Carnegie-Mellon University, it occurred to me that this procedure of computer programming and that of psychoanalysis were in fact very similar. Colby, a thoroughly trained analyst, was in fact programming belief systems on computers to simulate some of his patients in order to make better sense of the structure of the beliefs that determine our emotions and behavior. And Newal, together with Herbert Simon of Carnegie-Mellon, was simulating the thinking process with this new technology much as the Wurtzberg school of psychology had done a century earlier. I became intrigued by this correspondence and found that indeed Freud had benefitted from the Wurtzberg experience through his academic courses with Brentano, the famous Viennese philosopher who inherited the mantle of problems left by the thought analysts. Freud's training was therefore not only neurological but « behavioral » as well — at least as behavioral as Newal's, Simon's and Colby's — all highly respected scientists today. The psychoanalytic technique, was thus for him, scientific, and as I have tried to point out on various occasions, the psychoanalytic model is based on operational definitions and on neurological and behavioral data. As such it is open to modification by new data when these become relevant. Revisions, fresh looks at the model are long overdue in face of the wealth of research that has been accomplished in the past half century.

There is good reason to believe that the brain functions in a fashion which is in some essential respects similar to the operations of a computer. My own evidence suggests that the limbic formations and the frontal cortex are especially concerned with this programming process. I began my brain research to learn more about frontal lobotomy which was a popular procedure during the days of my training as a neurosurgeon, despite our then woeful ignorance of the functions of the frontal cortex. I recently summarized the ensuing twenty years of research with the suggestion that this cortex acts as an executive for the rest of the brain much as an executive functions in modern time sharing computer systems. This summary statement is now subject to specific testing since we can be very precise about the operations of such executives. We already have the evidence from the orienting reaction experiments summarized above to give direction to the investigation. As mentioned, the frontal and limbic structures are involved in the directive aspects of attention. It is not farfetched to suppose that this same directive process can function internally to address memory, though just how, by what mechanism this is accomplished has still to be determined. We do have evidence, however, that these structures are involved in organizing the relevant aspects of situations according to whether they have in the past been right or wrong, rewarding or punishing. And we also have evidence that the neural signals generated by this reinforcing process reach the primary projection systems where they can operate on the rest of the memory mechanism.

I believe that I have detailed enough here to give some feeling for the type of investigation now possible in the sciences of mind. Progress has been prodigious and I have mentioned only some of the interesting developments. There are many others. I remember in college asking in my physiology course about the mechanism of thirst. Little was known. Today it is clear that thirst is dependent on an osmosensitive receptor mechanism which lies near the base of the third ventricle in the hypothalamic region of the brain. Other receptors surrounding the midline ventricular system are sensitive to temperature, sex hormones, blood sugar level and the like. Sleep, wakefulness, even aggression and depression, are being found to be dependent on such specific receptor sites in the upper brain stem.

So, I could go on. Right now language itself is in the foreground of investigation. Linguistic, analytical philosophers have been proclaiming that mind is language, and computer scientists have been creating languages and insisting therefore that their computers, once programmed, have minds of their own. And sometimes indeed it seems that way when one has made an error in programming and is told by the machine « Try again! ».

This matter of mind is not just an academic issue. Recently two Mobil Oil scientists developed a spectographic analysis carried out by means of a program to work on a general purpose computer and tried to patent it. The patent office rejected the application on the grounds that a program was a « mental process » which is unpatentable. The U.S. Supreme Court of Customs and Patent Appeals ruled, however, that a computer program can change an already patented general purpose computer into a special purpose machine that is eligible for a patent.

No, the problems of mind are far from being completely resolved. But then, some of us « prefer to live on the ragged edge » ... and « gnaw the file forever », as William James put it. What makes this experience so nerve wracking as well as rewarding is that the scientific endeavor demands the repeated painstaking scrutiny of details of procedure and data to see whether they can be viewed from some new vantage. Note that this is what made review of the experimental results on the orienting reaction so interesting. If one reads only for *words* such as arousal, attention and memory, one misses the intimate and intricate relationship between them which has been *demonstrated* by the experiments and makes up the *language* of science. And what is even more important, one misses the feel and fun that science can be, the fun currently provided in such large measure by the sciences of mind.