T-118

DÆDALUS

Journal of the American Academy of Arts and Sciences

Intellect and Imagination
The Limits and Presuppositions of Intellectual Inquiry

SPRING 1980: INTELLECT AND IMAGINATION—THE LIMITS AND PRE-SUPPOSITIONS OF INTELLECTUAL INQUIRY

Issued as Vol. 109, No. 2 of the Proceedings of the American Academy of Arts and Sciences

KARL H. PRIBRAM

The Role of Analogy in Transcending Limits in the Brain Sciences

IT IS 1980 AND ONLY TWO DECADES before the turn of the millennium. I wonder whether the term "limits" in the subtitle of this symposium reflects the recurrent fear humanity expresses as it approaches millennial transitions. The last two decades have been populated by prophets of doom who reflect in a more sophisticated way the projections of the end of the world rampant in the years 975-1000.

During these past decades I have been fortunate to participate in the unprecedented growth of knowledge about the human brain and how it makes possible human behavior and even human experience. Thus, I find it difficult to entertain *any* notions of limits in my field of inquiry. To paraphrase Wittgenstein, "The limits of my brain" are the same as "the limits of my world." But, in fact, only logic is limited; the world of emotion and practice is limitless. Gödel in his famous "proof" showed that any self-contained logic cannot prove true or false—that is, meaningful. What he failed to point out is that truth and falsity *can* be established when such a logic addresses events or contexts outside itself.

Formal logic of the mathematical kind is a result of categorizing and of the image-making and information-processing abilities of the cerebral cortex of the brain. These abilities involve contextualizing processes that relate image, information, and logic to use. During the past quarter century studies of brain function have gone beyond logic derived from analysis of the nervous system and now include the results of discoveries in other fields: communication theory derived from the operation of telephone systems; control mechanisms as developed in cybernetics; information processing as performed by computer programs; and image processing as demonstrated optically. From these discoveries new reinterpretations of familiar data and ways to search for new data have developed.

The surge of understanding that has come to the brain sciences has been almost overwhelming. Can the human brain fruitfully inquire into its own thought processes? When our understanding is stretched, we are tempted to draw the line—in this instance to interpret recent history as a terminal flowering of Western thought. We could conclude that the brain, man's last frontier, has shown us man's limits. I prefer, however, to look on the latest expansions of brain science as another example of the horizons that can be penetrated when human brain meets human brain.

On the Use of Analogy

Over the past century our civilization has produced several inventions that have initiated novel modes of thought. Each invention has had extensive practical consequences that have altered our daily life. Perhaps as significant in the long run are the modes of thought that accompanied or initiated the inventions, for these modes of thought form the context, the matrix, of the future: novelty is conceived in familiarity; inventions flow from taking inventories.

This essay addresses the impact of the new modes of thought on conceptions of brain structure and function, especially in their relationship to thought processing. The essay is therefore an attempt to trace the manner in which human brains go about understanding themselves. Skeptics suggest that such understanding in any nontrivial sense is impossible. Here I argue that a certain kind of understanding can be achieved on the basis of past accomplishments.

The kind of understanding to be gained is what is usually called "scientific." When I listen to a symphony or feel the intimacies of a relationship or enjoy a good meal, I experience a sense of tacit understanding of the symphony, the interpersonal experience, the food before me. This sort of existential understanding can be complemented by the study of musical form and of the ear and auditory nervous system; the analysis of the constraints and freedoms in interpersonal relationships and the emotional and motivational makeup of the persons involved; or the caloric content and constituent composition of foods and their metabolism. Such knowledge does not detract from, and may even enhance, each of the existential processes described. It is clear, however, that existential understanding is essentially private, while scientific understanding is essentially and eminently shareable.

Once we distinguish between existential and scientific understanding we can see that the skeptics are indeed correct in doubting our ability to achieve an existential understanding of our own brains. Brain tissue is peculiar because, in contrast to other tissues, it is largely insensitive to probing even by neurosurgeons. We cannot, therefore, sense our brains as such. Only the brain's processes are accessible to experience. As an example, when the somatosensory area of the cortex is electrically stimulated, a sensation of tingling in the toes is produced; when the classical motor region is excited, the toes actually move. In epileptic patients, whole trains of remembered experiences can be elicited when the cortex of the temporal lobes of the brain is probed electrically. The patient never exclaims that he feels his brain. He simply feels, and that feeling is referred to those parts of "him" that make neuronal connections with the brain tissue under the probe.[1]

Yet, while the brain appears inaccessible to existential understanding, there seem to be no barriers to a scientific understanding. As in other scientific endeavors, such understanding comes from a propitious blend of the three modes of reasoning that guide research and provide some understanding of its results: the induction of principles from data; the deduction of logical relationships among principles; and reasoning by analogy, which attempts to place the relationships in a wider context. This essay is chiefly concerned with reasoning by analogy, because, as pointed out by C. S. Peirce,[2] innovation stems almost exclusively from the proper use of analogy. Induction systematizes the familiar;

deduction casts it into formal relationships. Reasoning by analogy, on the other hand, brings to bear on the familiar a new perspective derived from another realm of inquiry.

The use of analogy has been fruitful in the brain sciences from their beginning. Often the analogical thinking is implicit. Sometimes it is explicit, as when the brain is compared to a telephone switchboard or to the central processing unit (CPU) of a computer. In either case, the analogy provides a step in the understanding of how the human brain functions.

On the Telephone and Information Measurement

The contribution of telecommunications to brain science came in the form of techniques for measurement of the flow of signals. The contribution of Bell Laboratory's Claude Shannon and his collaborator Warren Weaver[3] is a landmark in the development of modern thinking. Shannon and Weaver developed a measure of signal patterns in impulses of energy transmitted over a given time in a limited communication channel, using a binary Boolian algebra as a base for that measure. Thus a BIT (*bi*nary dig*it*) of information was first conceived as a unit indicating the match between the signal patterns produced by a sender and those received at the other end of the communication channel. The measure of information related the number of possible understandings (alternatives) contained in the message to those that actually were understood by the receiver. When the number of alternatives or possibilities (uncertainties) had been reduced by half, one BIT of information was said to have been transmitted. Shannon and Weaver noted that such a measure was related to the idea of entropy. Entropy measures the disorder of a system. The idea is taken from thermodynamics where it is used to describe the efficiency (or inefficiency) with which energy is used by a machine. Measures of order in the use of energy and in the flow of information promised to yield interesting results when applied to other fields of inquiry.

But this line of thinking ran into difficulties. Shannon noted that the measure of information depends on the uncertainty (the number of alternatives) in a system. For him, the measures of information and entropy were positively correlated—more information implies greater entropy. However, others, like Brillouin,[4] pointed out that an increase in the measure of information involves uncertainty *reduction* and is therefore more appropriately related to the opposite of entropy. This view has become prevalent: information is now conceived as the measure of order, and entropy as the measure of disorder, of a system.

In the brain sciences the information measurement concepts became especially powerful in the hands of Warren McCulloch and his collaborators.[5] They described the brain as an organ where communication functioned both internally in the network of neurons and as a means of providing the order of external (psychological) communications between individuals.

The impact of these formulations has been paradoxical. On the one hand, the idea has taken root that a level of organization beyond that of electrical nerve impulses exists and can be dealt with in quantitative terms as "information." On the other, specific contributions of information measures to the understanding of brain function or to psychology have been meager. Ross Ashby, one of the foremost exponents of information measurement theory, has remarked that the strength of the theory does not lie in providing answers but in allowing the reformulation of questions in more precise terms.[6]

The concept of channel capacity is an example of the failure of information measurement theory to provide specific answers while sharpening the framing of questions. This concept was devised to handle the organization of energy patterns in fixed channels of limited capacity. But this is an oversimplification in brain science, because fixed channels of limited capacity do not exist in the brain,[7] nor do they operate in personal communication[8] where the context of transactions is continually influenced by information received. Neurological and psychological systems operate within flexible constraints that shift, expand, and contract, as they do, for instance, when attention becomes focused. It is a common mistake at present to attribute *all* processing limitations to restricted channel capacity.[9] Although central brain processing limitations are real,[10, 11] the idea of "competency,"[12, 13, 14] based on contextual structuring, or "*chunking*" as suggested by Miller,[15] Simon,[16] and Garner,[17] is more productive.

The move from a concept of a restricted channel capacity to the concept of a flexible competency capable of being "reprogrammed" to meet changing conditions heralds a shift from viewing the brain as a telephonelike system to regarding it as computerlike. Before taking up this shift we need to clarify another related problem plaguing the application of information measurement theory.

On the Thermostat, Feedback, and Cybernetic Control

Cybernetics, "the science of information and control,"[18] raises the new problem. Intuitively, we may feel that the greater the amount of information available to a system, the more precisely that system can be controlled. However, since information can be defined as a measure of the amount of uncertainty in a system (as suggested earlier), it would appear that the more information there is present in a system, the harder that system actually is to control.

The difficulty is resolvable. Shannon in his original paper distinguished between two types of information: the first reduces uncertainty; the second is concerned with repetitions. In a telephone communication disturbed by excessive noise, the receiver often shouts, "What did you say? I can't hear you. Please repeat." When the sender hears this, he will repeat the message. The effect of repetitions is to reduce noise and error, and can be measured separately from reducing the uncertainty contained in the original communication. Error reduction is accomplished by repetition, or redundancy, rather than by changing the structure of the communication. Since error-reducing signals were not an intrinsic part of uncertainty-reducing communications, they were of secondary concern to Shannon and Weaver. However, error-reducing signals are, as we shall see below, the critical operators in control systems.

The original idea behind cybernetic control systems is twofold: (1) the current state of a system can be compared with a desired state, and (2), the current state can be brought closer to the desired state through adjustments (repetitions) based on the magnitude of an "error signal" that denotes the discrepancy between the current state and the desired state. The process of adjustment that reduces the error signal is called "negative feedback."

Norbert Wiener in *Cybernetics*[19] notes the relationship between cybernetics and the concept of homeostasis. Homeostasis describes the maintenance of a constant internal environment in the body by compensatory mechanisms brought into play when shifts occur in chemical or physical conditions. The physiologist Cannon[20] had developed this concept extensively. Wiener included physiological homeostasis in the broader concept of control systems. The thermostat, which maintains a temperature within assigned limits, is an example of a control system.

The idea of physiological homeostasis played a role in the development of the more comprehensive ideas of cybernetics. The concept of negative feedback that developed out of control systems is, in turn, applicable to neurophysiology. In a sense, an engineering idea that was, in part, based on physiological observations returns to physiology on a higher level. Negative feedback is currently invoked to explain regulation by the brain of sensory input from the external environment[21] and the fine-tuning of muscle activity.[22, 23]

The first evidence of negative feedback in the operations of the nervous system came from work on muscle spindles, receptors in the muscles that signal the degree of muscle stretch.[24, 25] These muscle spindles are directly controlled from the spinal cord and brain, forming a loop that assures that movements are smooth and coordinated.

Feedback from the brain also regulates receptors of other sensory systems. Signals originating in the brain can alter the input of signals from tactile,[26] auditory,[27] olfactory,[28] and visual[29, 30] receptors. The association areas of the brain, which lie adjacent to the somatosensory cortex, are potential sources of these signals that influence sensory input.[31, 32, 33]

This evidence of central control over receptors revolutionized the concept of the reflex[34] in neurophysiology and thus affected the picture of the stimulus-response relationship that had dominated psychology for decades. No longer could the organism and its brain be thought of as a passive switchboard upon which environmental contingencies might play at will. A new, active image of a self-setting, homeostatically controlled organism that searched for and selectively accepted environmental events replaced the old passive stimulus-response image. Now, instead of responses elicited by discrete stimuli, as in the old physiology and psychology, the response was seen as initiating further nervous system activity that altered future responses. In biology, this change in thinking flourished in the studies of animal behavior known as ethology. In psychology, the change was reflected in an abandonment of stimulus-response learning theories in favor of the ideas of operant conditioning and cognitive conceptualization.[35]

The thermostat embodies these principles. The set point of the thermostat determines the level at which changes in temperature will be sensed by the system and regulates (starts and turns off) the operation of the furnace. Here, the operation of the furnace depends on temperature changes within chosen limits rather than on a simple on-off switch. Homeostatically controlled systems, like the thermostatically controlled furnace, provide a tremendous saving in memory load. Von Foerster[36] called this mechanism a "memory without record." There is no need to keep track of the vagaries and variabilities of the temperatures external to the system: the homeostatic system operates on the hottest summer days and in the coldest winter months. Only the deviations of temperature from the set point need be sensed.

Cybernetics attempted to combine the insights derived from telecommunications with those derived from servocontrol. As noted earlier, this created problems. Some of these were anticipated by Shannon[37] when he used the term *information* in two different technical senses, neither of which corresponds to the popular sense. As we have seen, in one technical sense information is a measure of the reduction of the number of alternative choices, that is, of uncertainty. In the second, information was used to denote a measure of the failure to reduce a discrepancy between two ongoing processes. But the distinction goes even deeper. The first measure specifies chiefly the complexity of a process. It can be precisely and quantitatively stated in bits. The second measure is an error signal that specifies little or nothing about complexity, but deals only with discrepancy and changes in discrepancy. Usually it is measured in continuous analogue terms, since it is *change* that is of central concern. As noted above, when digital measures are applied to this second kind of information, it is seen to be more akin to the concept "redundancy" than to the concept "information"! It is this redundant error signal that is the critical component of homeostatic mechanisms and is involved in the negative feedback process of cybernetic control systems.

Error signals, which specify changes in redundancy rather than in uncertainty, provide the link between cybernetic concepts and information measurement theory. Cybernetic systems use redundant error signals to maintain stability. They have little to do with "uncertainty" or complexity. Brain systems that operate solely on homeostatic principles are technically not information-processing systems in the sense of reducing or enhancing uncertainty. Information measurement theory is therefore not applicable to internal homeostasis and external sensory processing unless the homeostatic principle is supplemented in some way.

These ideas characterized the brain and behavioral sciences two decades ago and are detailed in *Plans and the Structure of Behavior*.[38] Roger Brown[39] rightly criticized this book for the homeostatic cast it shares with psychoanalytic theory.[40] The notion of "drives and habits" in Hullian stimulus-response psychology and Skinner's concept of the "conditionable operant"[41] share this slant. Even ethological formulations of "eliciting stimuli" and "action specific energies" are essentially modeled on the homeostatic principle.[42, 43, 44] But the capacity of homeostatic systems to alter their set points is implicit in all of these theories.[45] This capacity was emphasized by Waddington in his concept of homeorhesis: a flow toward an ever-changing set point rather than a return to a static stable one.[46] Homeorhetic systems are open, helical, future-oriented, feed-forward systems (as opposed to homeo*static* systems, which are closed loops) because the changes in set point can be programmed. In biological systems, prime examples of helical organizations are the DNAs that program development. Engineers have developed nonbiological programmable systems, the currently ubiquitous computers.

On Computers and Programming

Computers are information-processing devices that have been heralded as harbingers of the second industrial revolution, the revolution in the communication of information. This revolution can be compared with the communications revolution that occurred at the dawn of history with the invention of writing or, earlier, when linguistic communication between humans began. The current revolution depends largely on stepwise serial processing. Despite prodigious speed, serial processing is considerably less nimble than the brain's facility, which, as we shall see, is based to a large extent on parallel procedures carried out simultaneously. Nevertheless, as a model for brain activity, computer programming has produced two decades of intense research.[47, 48, 49, 50] More recently, the field of artificial intelligence has attempted to enhance computer capabilities by patterning computers after natural intelligence[51] or possible brain organizations.[52] What has generated such wide-sweeping changes in the way we view communication and computation?

Von Neumann contributed a major innovation by devising a system of lists in which each item in a list was prefixed by an address and suffixed by an instruction to proceed to another address. This system allowed any item in any list to be addressed by (follow) any other item and in turn to address (precede) any other item. Items and lists of items therefore became endowed with the capacity to address themselves (often after running through several other lists), called "recursiveness" in the jargon of programming. As Turing pointed out,[53] self-reflective programs endowed with recursiveness can locate any item stored in them and can associate any group of items. Such a network of lists is a far cry from the stimulus-response type of communication based on the model of the early simple telephone connection.

Structures embodying lists of the sort necessary for program construction have been shown to occur in the brain cortex. The cellular organization of the cerebral cortex of the brain shows both a vertical and a horizontal patterning. There are vertical columns of cells, perpendicular to the surface of the cortex, in which each cell responds to a different aspect of sensory input from a small group of receptor cells on the surface of the body, from a small area of the retina, for example. The columns can be thought of as lists containing items (the cells).[54, 55] The horizontal organization of the cortex reflects the arrangement of receptors on the surface of the body. The somatosensory area of the cerebral cortex, which lies directly behind the central fissure, receives sensory signals from the body surface projected in a pattern that mimics a tiny human figure, or "homunculus." The items (cells), therefore, also form horizontal lists. Interconnections between the cells in columns or arranged within a single horizontal layer enable the brain to interpret moving sensory signals. Thus some cells in the vertical lists show sensitivity to movement of the stimulus from one surface touch receptor to another. Movement in one direction can trigger the brain cells, while movement in another has no effect, a finding that can be interpreted as suggesting a set of prefixes and suffixes as in von Neumann's analysis.[56, 57] In the visual part of the cortex *each* cell (item) in the cortical column (list) appears to be endowed with such prefixes and suffixes. Most of these cells respond selectively to movement, direction, and even velocity changes,[58] which suggests a richer, more finely grained network of connections than is present in the somatosensory system.

Characterization of cortical cells of the brain as similar to items in a program list is often described as *feature analysis*, since each item represents one feature of a sensory input. In fact, the prevailing school of neurophysiological thinking currently favors the view that these cells are feature detectors,[59] that is, that each brain cell is uniquely responsive to one—and only one—feature. A competing view is that each cell has multiple selectivities and that its output is not unique to any one type of stimulus, as would be required of a feature detector. In the visual cortex, for example, a cell may select on the basis of the orientation of lines, their width and spacings, luminance, color, the direction of movement, the velocity of movement, and even the frequency of auditory tones.

It appears, therefore, that each cortical cell is a member of an associative network of cells (perhaps a set of list structures, as the evidence noted above would suggest) rather than a single feature detector. *Feature analysis* must therefore be a function of the entire network of cells that is addressed by the total pattern of sensory input. The brain thus differs from current computers in that the initial stages of processing occur simultaneously, that is, in parallel rather than serially. Feature analysis, therefore, results from pattern matching rather than from single feature detection. To return to an earlier analogy, the thermostat is a primitive pattern-matching device that "selects" deviations from a set point. It thus reduces the memory load that would otherwise be required to "detect" the occasion of each and every new temperature that required a response. An association of homeostatic devices, that is, columns of brain cells, thus can serve as pattern-matching devices that select features from the sensory input.

Even the concept of list structures of homeostatic devices does not solve all the problems raised by viewing the brain as an associative network of cells. Ashby[60] noted that such associative networks tend to be hyperstable and thus intolerably slow to modify; they seem to be unable to learn. To paraphrase Lashley,[61] even though one may be driven at times to consider such a model in the classroom, it should not be forgotten that one of the brain's distinguishing features is its capacity to learn. Two choices are open to the model-builder. He can ignore the evidence for homeostatic organization of the brain, as Mountcastle and Edelman have done in their proposal for a "degenerative" (a many-to-one mapping) model in which feedback becomes a secondary rather than a primary constituent.[62] He can also do as Ashby[63] and as Miller, Galanter, and I[64] have done—start with an associative net made up primarily of homeostatic elements and add constraints. These constraints are based on invariant properties of the stimulus. The structures within the brain that recognize invariant stimuli or test-operate-test-exit units (TOTES as Miller, Galanter, and I call them) cut the associative net into pieces (to paraphrase Ashby) and can be shown to be organized hierarchically.[65, 66, 67, 68] A definition of the "invariant properties," or features, of stimuli now becomes critical. Turvey[69] and Gibson[70] describe such properties as localized in the environment of the organism, while nativists (for example, Chomsky[71]) describe them as selected by the organism in the face of an environmental cornucopia. The computer model of brain structure and function suggests an intermediate stance. In a computer the selection of a workable program depends on a "good fit," a match between input and central processor. The brain's "central processor" may be considered to have become adapted during evolution to an ecological niche, and it should be possible to determine the "invariant properties" (features) of that niche that have effected the adaptation. But with as general purpose a computer as the human brain, the responsible environmental features may be as difficult to delimit as the specifications of the adapting mechanisms of the brain that are concerned with identifying these invariances.

On the Hologram and Pattern Analysis

Mechanisms of extracting invariances ("features") from sensory input have been of considerable interest to neuroscientists and psychologists. As we have seen, a brain cell organization based on an associative net with hierarchic constraints can serve as a useful model. Certain problems exist with this model. There is, for example, the need to postulate an analytic mechanism that is relatively sparing in its use of neurons so that invariance can be detected without invoking a "one neuron-one feature" equivalency. A successful model must also explain the speed and immediacy[72] with which perception occurs and its high resolving power.

Historically, three sorts of answers have been given to the question raised. At one extreme is the "feature detector," or "one neuron-one feature" answer, which, as noted above, is untenable in the light of currently available neurological evidence. This model can also be faulted from behavioral evidence.[73] At the other extreme is the model proposed by Wolfgang Köhler to account for the distortions of physically measured stimulation found in illusions. Köhler emphasized the configurational aspects of perception, and suggested that direct current (D.C.) fields result when sensory input arrives in cortical tissue. The low resolving power of the D.C. fields casts doubt on the efficacy of such machinery and its ability to account for texture perception. A series of experiments was therefore set up to test the issues involved. The results of these experiments showed: (1) D.C. shifts *did* accompany the desynchronization of the cortical electrical record (EEG) induced by sensory (visual and auditory) stimulation; (2) disruption of D.C. electrical activity by epileptogenic agents placed on, or injected into, the cortex failed to impair pattern perception; and (3) such disruption did impair learning. Subsequently, it was shown that imposing a cathodal (negative) D.C. polarization across the cortex would slow learning, while imposing anodal (positive) D.C. polarization would speed learning.[74] In short, direct current shifts in the cortex bias learning, not perception, and are thus unlikely candidates for the critical machinery of pattern perception.

Between the extremes of the "one neuron-one feature" (usually referred to as the "pontifical" or "grandfather" cell dogma) and the D.C. field theory, a pair of more moderate views has been proposed. Each of these stems from one of the extreme positions. Neurophysiologist Horace Barlow[75] has suggested that the idea of "one neuron-one feature" be dropped in favor of a set of cells that together can recognize a feature. This proposal is little different from that made by psychologist Donald Hebb,[76] who suggested that a cell assembly becomes constituted in response to sensory input. In these proposals "one neuron-one feature" is replaced by "one cell assembly-one feature." Barlow's and Hebb's proposals differ in that Barlow's cell assembly has a relatively fixed range of sensitivities—propensities to respond—while Hebb's "phase-sequenced" cell assemblies vary with respect to their constituent neurons and change with experience.

A quite different point of view was offered by Karl Lashley in his proposal that waves of activity are generated in the cortex by sensory input and that these waves interact to produce interference patterns. Lashley, however, did not develop his suggestion at either the neuronal or the perceptual level. He was attracted by the possibility suggested by Goldscheider[77] at the turn of the century that the brain's organization of the perceptual field might display some of the same characteristics as the organization of embryonic developments (Lashley was a zoologist by training).

In several works I have developed in detail the "interference pattern" model for brain function.[78, 79, 80] At the neuronal level, the model interprets electrical changes in the cell membranes of neurons on the far side of synapses (or interneuronal junctions) as constituting wave fronts. These electrical changes, known as "hyperpolarizations" and "depolarizations," are not themselves nerve impulses. Depolarizations increase the likelihood that a neuron will increase its generation of nerve impulses; hyperpolarizations decrease this likelihood. My proposal is somewhat similar to that made in quantum physics where the wave equation is treated as a vector based on the probability of occurrences of quantal events. The neural "quantal events" are those hyperpolarizations and depolarizations that, taken as a pattern occurring in an area of the cortex, can be described in terms of wave forms. These patterns of polarizations form microwaves. They are not to be confused with the macrowaves that compose the electroencephalogram (which do not have the resolving power necessary to account for the richness of texture of perception). The EEG wave forms reflect the sum of many microwave processes as well as any synchronized nerve impulse activity found within the field of a recording electrode.[81, 82, 83] Molecular storage, perhaps in the form of a conformational change in the proteins of the cell membranes at neuron-to-neuron synapses, is assumed to result from repetitions of particular microwave patterns.[84, 85]

At the perceptual level, the model implies that sensory input becomes encoded in synaptic membranes by microwave patterns in such a fashion that image reconstruction can be readily accomplished. This can be done by storing the Fourier or similar transform (see below) of a sensory signal (which involves storing the phase relationships as well as the intensity of the signal[86]) rather than representing it by simple point-to-point intensive dimensions. (Compare this to a movie of the ripples produced in a pond by a set of pebbles thrown in.) In order to read out an image from such a store, all that is necessary is to invoke the inverse transform (actually the identical mathematical operation in the Fourier procedure) to restore an image. (Compare this to running the movie of the pond surface backward until the pebbles reappear.)

Evidence has been accumulating for almost a century that such wave form descriptions of sensory processing are valid. Ohm (of Ohm's Law) suggested in 1843 that the auditory system operates as a frequency analyzer, perhaps according to Fourier principles. Fourier theory states that *any* pattern, no matter how complex, can be separated into a set of component sine waves, that is, a set of completely regular wave forms, each at a different frequency. Helmholtz developed Ohm's suggestion by a series of experiments that provided evidence that such separation takes place in the cochlea, the part of the inner ear where the sound receptors are located. Helmholtz proposed that the cochlea operates much like a piano keyboard, a proposal that was subsequently modified by Georg von Bekesy,[87] who demonstrated that the cochlea resembled more closely a stringed instrument brought to vibrate at specific frequencies. Nodes of excitation developing in the vibrating surface (the "strings") accounted for the piano-keyboardlike qualities described by Helmholtz.

Bekesy further developed his model by actually constructing a surface bearing five vibrators, which he placed on the forearm of a subject. The periods of vibration of the five vibrators could be adjusted so that the five showed a variety of phase relationships to one another. The phase relationship could be adjusted so that a single point of tactile excitation was perceived.[88] It was then shown that the cortical response evoked by such vibrations was also located in a single area: the pattern evoked resembled the perceptual response in its singleness rather than the multiplicity of the physical stimuli.[89] Somewhere between skin and cortex, inhibitory (hyperpolarizing) interactions among neurons had produced a transformation. Bekesy went on to show that by applying two such vibrator-bearing surfaces, one to each forearm, and once again making the appropriate adjustments of phase, the subject could be made to experience the point source alternately on one arm, then on the other, until, after some continued exposure, the source of stimulation was projected outward into space between the two arms. Bekesy noted that we ordinarily "project" our somatosensory experience to the end of writing and surgical instruments. The novelty in his experiments was the lack of solid physical continuity between the perceived source and the actual physical source. Stereophonic high-fidelity music systems are based on a similar principle: by appropriate phase adjustment, the sound is projected to a location between and forward of the acoustical speakers, away from the physical source of origin.

Over the last decade it has been shown that the visual system operates along similar principles in its processing of spatial patterns. In an elegant series of experiments, Fergus Campbell and John Robson[90] found anomalous responses to sets of gratings (sets of lines or bars) of various widths and spacings. The anomalies were reconciled when it was realized that the widths and spacings of the bars could be treated as having a frequency of alternation over space—that is, the width of bars and the distance between them formed a pattern that, when scanned, showed a frequency in the change from bar to spacing. The anomalous results were obtained when these "spatial frequencies" formed harmonics.

Currently, it has been shown that certain cells in the visual cortex encode such "spatial frequencies."[91, 92, 93] Most telling are the results of experiments pitting the standard neurophysiological hypothesis that these cortical cells are line (bar or edge) detectors against the hypothesis that they are selective of one or another band width of spatial frequency. DeValois showed that cortical cells were insensitive to bar width and that, when the bars were crossed with others in a pattern such as a plaid, the response of the cortical cells changed to reflect the total pattern. Specifically, each cortical cell was shown to be selectively sensitive to lines (gratings) oriented in a particular direction, a finding[94] that had been instrumental in generating the feature detector proposal. If the cells were operating as feature detectors, additions to the initial display pattern of lines should not alter the orientation in which the display has to be shown in order to match the selectivity of the cell. Additional lines in the pattern would be processed by additional units whose orientation matched that of the additional lines. If, on the other hand, the total pattern of the plaid was being processed by the brain cell, the orientation of the whole pattern would have to be altered to match the orientation of the major components of the Fourier (i.e., spatial frequency) transform of the pattern. DeValois performed a Fourier transform by computer on each plaid displayed. Such transforms showed radii at various angles from the original perpendicular pattern of the plaid. DeValois found that all plaid display patterns had to be rotated to bring these radii into line with the special selectivity for orientation of the brain cells. Furthermore, the rotation was exactly that (to the degree and the minute of visual arc) predicted by the proposal that the Fourier transform of the total plaid (and not its separate lines) is encoded.

There thus remains little doubt that descriptions of the quantal microwave form domain in the cortex are valid models of the processing of sensory stimuli in audition, touch, and vision. Such descriptions can also be compared to image formation in the processing devices called holograms. Holograms were so named by their inventor, Dennis Gabor, because each part of the hologram is representative of the whole. In a hologram each quantum of light acts much like a pebble thrown into a pond. The ripples from one pebble spread over the entire surface of the pond (the mathematical expression for this is in fact called a spread function—the Fourier transform is a prime example of such a function). If there are several separate pebbles, the ripples produced by one pebble will originate in a different location from those produced by another pebble. The result will be that the ripples will intersect and form interference patterns, with nodes where the ripples add, and sinks where they cancel. If the "ripples" are produced by light falling on film (instead of pebbles falling into water), the nodes can be captured as reductions of silver grains on the film. Note that the information from the impact of each pebble or light ray is spread over the "recording" surface; thus *each portion* of that surface can be seen as encoding the whole. And as noted earlier, performing the inverse Fourier transform reconstructs the image of the origin of that information. Thus the whole becomes enfolded in each portion of the hologram since each portion "contains" the spread of information over the entire image.

The principle of the hologram is different from the earlier Gestalt view that wholes develop properties in addition to the sum of their parts. The properties of holograms are expressed by the principle that "the whole is contained or enfolded in its parts," and the very notion of "parts" is altered, because parts of a hologram do not have what we think of as boundaries.

The properties of holograms that are important for brain function are: (1) the widespread distribution of information—a characteristic that can account for the failure of brain lesions to eradicate any specific memory trace (or engram);

(2) the tremendous storage capacity of the holographic domain and the ease with which information can be retrieved—the entire contents of the Library of Congress can currently be stored on holofische (microfilm recorded in holographic form), taking up no more space than is contained in an attaché case; (3) the capacity for associative recall that is inherent in holograms because of the coupling of separate inputs; and (4) the provision by this coupling of a powerful technique for correlating—cross-correlations and autocorrelations are accomplished almost instantaneously.

It is important to realize that holography is a mathematical invention and that its realization in optical systems through the use of laser beams is only one product of this particular branch of mathematics. Fourier transforms play a role in modern computer technology as in X-ray tomography and, as demonstrated by the evidence described above, in understanding the results obtained in experiments on brain function.

Let us return for a moment to the classes of neural models that have been proposed for perception. Recall that the quantal microwave model (i.e., of interference patterns, holography) derived from a dissatisfaction with both the "feature detector" and "cell assembly" theories. John[95] and Uttal[96] have also developed sophisticated statistical correlation models, which differ from the holographic model, however, in that they ignore the quantal microwave aspect of brain function. If the computer analogy of brain function is taken seriously, the most efficient manner of achieving statistical correlations is to transform the data (the sensory input, in the case of the nervous system) into the Fourier domain. There is thus a convergence of these models when they are followed to their logical and neurological conclusion: nerve impulses arriving at synaptic junctions are converted to postsynaptic depolarizations and hyperpolarizations, which can best be described as Fourier transforms of those impulses. Repetitions of impulse patterns result in information storage of as yet undetermined nature, possibly alterations in the cell membranes of neurons. Subsequent sensory stimuli are cross-correlated with the stored residual from former inputs, and the inverse transform of the results of the correlation form our perceptions. The perceptions are then projected away from the brain itself by appropriate phase relationships, as in Bekesy's experiments, in stereophonic sound equipment, and in holograms.

The fact that models involving patterns of quantal microwaves are valid for both brain function and holography does not, however, automatically assure the validity of the holographic hypothesis of brain function. There are important differences between the brain process and the optical information procedure. First, in an ordinary hologram the wave form is spread more or less over the entire surface of the film. In the brain each individual cortical cell reflects a particular pattern of depolarizations and hyperpolarizations on its postsynaptic membranes. If this is compared to wave form encoding in a hologram, it is seen that the cortical "hologram" must be a patchwork[97] in which the Fourier transform of any specific input pattern becomes encoded in an overlapping set of patches, each patch corresponding to the receptive field of a particular cortical neuron. But such composite holograms, called strip or multiplex holograms, are commonly employed to provide three-dimensional *moving* images.[98] The process of adding together strips representing Fourier transformed sections of space was invented by Bracewell[99] to compose a high resolution image of the heavens by radio astronomy. Pollen and Taylor[100] interpreted some of their neurophysiological results in terms of a strip hologram in which each elongated receptive field served as a strip in the total pattern. Thus the neural hologram, because of its patchwork nature, shows properties that are purely holographic (discussed below) as well as properties that are due to the spatial arrangement of the patches or strips. These spatial arrangements form the basis of the list structures described earlier and account for such nonholographic properties of perception as location and movement in the space and time domain.

Further, as noted earlier, each cortical cell is selective of several features of a stimulus. In the visual system these can include spatial frequency, color, directional movement, and velocity. Recordings from small groups of neurons in the visual cortex suggest that other aspects of situations are also encoded: in a problem-solving task, wave forms indicating the presence or absence of expected reinforcement are recorded.[101] The aspects of brain function that are encompassed by the neural holographic model are not exhaustive of all that the brain accomplishes, and the relationship of the model to the information and control models presented earlier must not be forgotten. The holographic model does, however, account for hitherto unexplained aspects of brain functioning, and it brings brain science into relationship with the revolution in modern physics occasioned by quantum and relativity theory.

This relationship to physics is brought out when a particularly vexing question is faced. In all of the holographic systems other than neural that have been described above, an observer is assumed. Who then, and where, is the observer of the image constructed by the neural hologram? Where is the little man in the head, who is the "I," the "self," that experiences the results of the holographic process?

To answer this question one must first ask what it is that is being observed. The assumption has been that an isomorphism (identical form) exists between a sensory perception and some physical "reality."[102] But, as the Bekesy experiment with multiple vibrators makes clear, physical reality and perceptual reality may differ substantially. The sensory apparatus appears to be lenslike as it focuses an input, but the focusing produces an image that is decomposed by subsequent neural activity into the Fourier transform domain—that is, into a distributed holographic form. In view of the invertability of *image domain ⇄ holographic domain*, one may ask in what form the input to the senses arrives? Is this input holographic in nature, and does it only become organized into images (thereby revealing the objects of which the images are formed) by the lenslike capabilities of our senses?

This view is probably too extreme. The only way we can answer these questions at present is through the evidence of the senses and the instruments devised to augment them. This evidence suggests an ordinary level of reality to which the senses have become adapted through evolution. "Ordinary reality" is the reality of Newton's mechanics and Euclid's geometry. It is grasped through consensual validation—by bringing to bear the several senses and inferring a reality that partakes of them all. We see a moon in the sky and send a man to palpate it. We bump into unseen obstacles and invent radar and sonar to discover them. As infants, we hear our mothers, and see and touch them. At another level, smell and taste are based on our perceptions of dissolved molecules —a chemical level of an unseen, unheard, and untouched reality.

More recently, physicists have probed ever smaller components and have taken a new look at the evidence about a spatially distant reality presumably palpable but beyond our reach. The evidence about this macrouniverse comes to us by way of the very same electromagnetic components that make up the microuniverse. It should come as no great surprise, therefore, that the laws that relate to us the nature of the macrouniverse, such as the special and general laws of relativity, and those that relate the nature of the microuniverse, that is, quantum and nuclear mechanics, provide a somewhat similar conception of reality. This reality, highly mathematical in nature, departs considerably from ordinary sensory experience.

David Bohm[103] has noted that, although the mathematics of relativity and of quantum theory are thoroughly worked out, the conceptual representation of what that mathematics might mean has lagged seriously. He suggested that this lag is owing to our propensity to use lens systems to construct our conceptual reality. He proposed that the hologram might provide a better conceptual model for understanding both the macrouniverse and microuniverse! His proposal strikes a responsive chord in the neuroscientist who also has found a level of organization in the nervous system that is more appropriately modeled by the hologram than by the senses (i.e., lenses). After all, the brain is a part of physical reality.

What are the characteristics of this holographlike order of reality? First, it does not correspond to sense perception and is thus counterintuitive. Second, this order—which Bohm calls "implicate" to distinguish it from the ordinary "explicate" sensory order—is nonobjective. The objective, explicate order is made up of the images by which we know objects. These images are constructed by lenses: the lenses and lenslike characteristics of our senses as well as the lenses, often called "objectives," of our microscopes and telescopes. By contrast, the holographlike implicate nonobjective reality is not composed of things but of quantally constituted microwaves and their interactive constituents such as constructive (nodal) and destructive interferences. Leibnitz described such a reality in his *Monadology*[104] in which the whole universe was represented in each monad, a windowless portion of the whole. Substitute lensless for windowless, and the monad becomes holographic.

Finally, in the reality described by the quantal microwave form domain, the ordinary dimensionality of space and time become enfolded (implicated), and a different set of dimensions becomes necessary in order to specify its characteristics. Time and space can be read out, but the readout may show peculiarities such as the complementary nature of measures of location in space and of moment (momentum), so that in specifying one, the other becomes elusive. "Particles" in this microuniverse appear to influence one another in situations where a causal connection between them cannot be traced.[105] An implicate order composed of the probabilities of appearance and disappearance of interactive nodes, related by their wave equations, was proposed to account for the peculiarities resulting from observations of the microuniverse. The implicate order is therefore not static, and "holographic" is a somewhat inappropriate term. A hologram is only a frozen record of an ever-changing scene. The term "holonomic," used in physics to describe linear dynamical processes, would be preferable.[106]

The fact that the holonomic implicate order is without boundaries; that every part enfolds or "contains" the whole; and that therefore the distinction between observer and observed is blurred so that observations no longer result in objects (i.e., observables) has led some physicists to note the intrinsic interweaving of perception and consciousness on the one hand and macrophysical and microphysical reality on the other. Thus Bohm includes an appendix on "Perception" in his book *The Special Theory of Relativity*,[107] and Wigner exclaims that modern physics deals with "relations among observations," not among "observables." An observable is characterized by invariance across observations; Heisenberg[108] in his famous principle pointed out that, in microphysics, the observed varies with the position and instrumentation of the observer. Bohr enunciated his principle of complementarity on the same grounds.[109] And, of course, Einstein made the same point with regard to the macrouniverse in his general theory of relativity. This enfoldment of observation into the observable has led some physicists, and some philosophers, Whitehead, for example,[110] into a panpsychism in which consciousness is a universal attribute rather than an emergent property of brain organization. Such views have interesting consequences for the analysis of the mind/brain issue,[111] bringing the concept of consciousness closer to that enunciated in the Eastern mystical tradition and the spiritual religious views of the West. Thus Capra[112] can proclaim a Tao of Physics in which the details of modern macrophysics and microphysics are matched to those of the mystical tradition. Science of this sort appears far removed from the objective operationism of the positivist and critical philosphers of the Vienna circle, for example, Carnap,[113] Feigel,[114] and their scientist heirs (e.g., Bridgeman[115] and Skinner[116]) of only a few decades ago.

On the Future

The major impact on the neurosciences of the views reviewed here has occurred in little more than a quarter of a century, between 1950 and 1975. The origins of these views can of course be traced into history. The shock waves produced by the impact have only begun to be felt in such intimately related endeavors as the behavioral sciences. Science as a catalogue of proximate causes in the Aristotelian sense, mechanistic in the Newtonian image, must give way to a science in which "final" causes are also searched and researched, and a science in which causality in the space-time domain must be, on occasion, suspended, if not generally superceded. A scientific endeavor dedicated to reducing all knowledge to CGS (centimeter, grams, seconds) dimensions will no longer suffice. Still, precision of thought and measurement, the hallmark of scientific as opposed to other knowledge, is not to be sacrificed. Science involves a sharing of knowledge, and sharing depends on replicability of results that in turn is based on precision. Pre-(s)cission, the analytical severing of part from part, is not enough, however, to deal with the new holism of the implicate order, nor even with the concept of gestalt or systems like computer programs. New multivariate approaches, enactment in addition to analysis (scission), new dimensions beyond the CGS are already being recruited into the practice of science. But integration of these new ideas into a "theory of science" is yet to come.

The impact on society of this approach to science is hard to anticipate. For example, the new views of the mind/brain relationship that have resulted from the changed concept of matter in modern physics and the "holonomic implicate" nature of the relationship of observer and observed can have dramatic consequences on man's view of himself, his nature, and his relationship to nature. A spiritual resurgence is certain to come, but just what form it will take and how it will affect our daily life is harder to predict. Medical practice may be completely revamped by holistic procedures: it is already established, for example, that placebos generate the endogenous secretion of the morphinelike endorphins in patients. Economics may take a new turn when holonomic principles are brought to bear. And even politics, the practice of the possible, may find the limits of the possible expanded beyond any current horizons.

There is no reason to expect that the sort of reasoning by analogy that has wrought the current revolution in science will cease. New developments, technical and theoretical, in engineering, chemistry, and psychology will continue to cross-fertilize the brain sciences—provided careful reasoning by analogy is fostered. The use of analogy in science involves taking a metaphor, using it to construct a precise model from inductively organized data, and testing that model deductively. If the past use of analogy presages the future, exciting discoveries lie ahead.

The advances in understanding in the brain sciences have been prodigious. One might even say that we have seen the last coming before Armageddon—a last glimpse of truth and beauty before our hubris destroys us. As we reviewed them, however, the brain facts themselves and the theories derived by the interactive functioning of human brains suggest a different, more optimistic stance. When what we have already learned has been assimilated into our culture, it will undoubtedly change the context within which further brain facts will be gathered and viewed. In the past such changes in context have continually renewed the human endeavor by providing new analogies. The way our brains are constructed gives us every expectation that such renewals will continue.

References

[1]See B. Libet, "Brain Stimulation and Conscious Experience," in *Brain and Conscious Experience*, J. C. Eccles (ed.) (New York: Springer-Verlag, 1966), pp. 165-81, for a review of the problems posed by his recent experiments in this fascinating area of investigation.

[2]C. S. Peirce, *Collected Papers* (Cambridge, Mass.: Harvard University Press, 1934).

[3]C. E. Shannon and W. Weaver, *The Mathematical Theory of Communications* (Urbana, Ill.: University of Illinois Press, 1949).

[4]L. Brillouin, *Science and Information Theory* (New York: Academic Press, 1962).

[5]W. S. McCulloch, "A Heterarchy of Values Determined by the Topology of Nervous Nets," *Bulletin of Mathematics and Biophysics* 7 (1945): 89-93.

[6]W. R. Ashby, *An Introduction to Cybernetics* (New York: John Wiley & Sons, 1963).

[7]K. H. Pribram, "Self-consciousness and Intentionality," in *Consciousness and Self-Regulation, vol. 1*, G. E. Schwartz and D. Shapiro (eds.) (New York: Plenum, 1976), pp. 51-100.

[8]G. A. Miller, "What Is Information Measurement?" *American Psychologist*, 8 (1953): 3-11.

[9]D. Kahneman, *Attention and Effort* (Englewood Cliffs, N.J.: Prentice-Hall, 1973).

[10]D. E. Broadbent, "Division of Function and Integration," *Neurosciences Study Program, III* (Cambridge, Mass.: MIT Press, 1974).

[11]K. H. Pribram, "How Is It that Sensing So Much We Can Do So Little?" *Neuroscience Third Study Program, III* (Cambridge, Mass.: MIT Press, 1974), pp. 249-61.

[12]N. Chomsky, "Formal Properties of Grammars," in *Handbook of Mathematical Psychology*, R. D. Luce, R. R. Bush, and E. H. Galanter (eds.) (New York: John Wiley & Sons, 1963), pp. 323-418.

[13]K.H. Pribram, *Languages of the Brain*, (Englewood Cliffs, N. J.: Prentice-Hall, 1971; 2nd edition, Monterey, Calif.: Brooks/Cole, 1977).

[14]K. H. Pribram and D. McGuinness, "Arousal, Activation and Effort in the Control of Attention," *Psychology Review*, 82 (2) (1975): 116-49.

[15]G. A. Miller, "The Magical Number Seven, Plus or Minus Two, or, Some Limits on Our Capacity for Processing Information," *Psychology Review*, 63 (2) (1956): 81-97.

[16]H. A. Simon, "How Big Is a Chunk?" *Science*, 183 (1974): 482-8.

[17]W. R. Garner, "The Stimulus in Information Processing," *American Psychologist*, 25 (1970): 350-8.

[18]At a conference I once posed the problem of specifying the relationship between information measurement and the control of systems to Norbert Wiener, Warren McCulloch, Don Mackay, and other cyberneticians. After many hours of discussion, everyone agreed that it was indeed a most perplexing issue that had at that time no direct answer.

[19]N. Wiener, *Cybernetics, or Control and Communication in the Animal and the Machine* (New York: John Wiley & Sons, 1948).

[20]C. Bernard, *Leçons sur la Physiologie et la Pathologie du Système Nerveux* (Paris: J. B. Bailliere et fils, 1858).

[21]K. H. Pribram, "The New Neurology and the Biology of Emotion," *American Psychologist*, 22 (10) (1967): 830-8.

[22]G. A. Miller, E. Galanter, and K. H. Pribram, *Plans and the Structure of Behavior* (New York: Henry Holt & Co., 1960).

[23]Pribram, *Languages of the Brain*.

[24]P. B. C. Matthews, "Muscle Spindles and Their Motor Control," *Physiological Review*, 44 (1964): 219-88.

[25]S. W. Kuffler, "Discharge Patterns and Functional Organization of Mammalian Retina," *Journal of Neurophysiology*, 16 (1953): 37-69.

[26]K. E. Hagbarth and D. I. B. Kerr, "Central Influences on Spinal Afferent Conduction," *Journal of Neurophysiology*, 17 (3) (1954): 295-307.

[27]R. Galambos, "Suppression of Auditory Nerve Activity by Stimulation of Efferent Fibers to Cochlea," *Journal of Neurophysiology*, 19 (1956): 424-37.

[28]D. I. B. Kerr and K. E. Hagbarth, "An Investigation of Olfactory Centrifugal Fiber System," *Journal of Neurophysiology*, 18 (1955): 362-74.

[29]D. N. Spinelli and K. H. Pribram, "Changes in Visual Recovery Functions Produced by Temporal Lobe Stimulation in Monkeys," *Electroencephalography and Clinical Neurophysiology*, 20 (1966): 44-49.

[30]D. N. Spinelli and M. Weingarten, "Afferent and Efferent Activity in Single Units of the Cat's Optic Nerve," *Experimental Neurology*, 3 (1966): 347-61.

[31]D. N. Spinelli and K. H. Pribram, "Changes in Visual Recovery Function and Unit Activity Produced by Frontal and Temporal Cortex Stimulation," *Electroencephalography and Clinical Neurophysiology*, 22 (1967): 143-9.

[32]S. L. Reitz and K. H. Pribram, "Some Subcortical Connections of the Inferotemporal Gyrus of Monkey," *Experimental Neurology*, 25 (1969): 632-45.

[33]M. C. Lassonde and M. Ptito and K. H. Pribram, "Intracerebral Influences on the Microstructure of Visual Cortex: Striatal and Cortical Effects on Response Properties of Visual Cortex Neurons" (submitted to *Experimental Brain Research*).

[34]Miller et al., *Plans and the Structure of Behavior*.

[35]Pribram, *Languages of the Brain*.

[36]H. von Foerster, "Memory without Record," in *The Anatomy of Memory*, D. P. Kimble (ed.).

[37]Shannon and Weaver, *The Mathematical Theory of Communications*.

[38]Miller et al., *Plans and the Structure of Behavior*.

[39]R. Brown, "Models of Attitude Change," in *New Directions in Psychology* R. Brown, E. Galanter, E. Hess, and G. Mandler (eds.) (New York: Holt, Rinehart & Winston, 1962), pp. 1-85.

[40]S. Freud, *Project for a Scientific Psychology*, 1895. (Standard Edition, vol. I, London: The Hogarth Press, 1966).

[41]B. F. Skinner, *The Behavior of Organisms* (New York: Appleton-Century-Crofts, 1938).

[42]K. Lorenz, "Innate Bases of Learning," in *On the Biology of Learning*, K. H. Pribram (ed.) (New York: Harcourt, Brace & World, 1969), pp. 13-94.

[43]N. Tinbergen, *The Study of Instinct* (Oxford University Press, 1951).

[44]R. A. Hinde, "Factors Governing the Changes in Strength of a Partially Inborn Response, as Shown by the Mobbing Behavior of the Chaffinch (*Fringilla Coelebs*)," "I: The Nature of the Response, and an Examination of Its Course," *Proceedings of the Royal Society*, B, 142 (1954): 306-31; "II: The Waning of the Response," *Proceedings of the Royal Society*, B, 142 (1954): 331-58; "III: The Interaction of Short-term and Long-term Incremental and Decremental Effects," *Proceedings of the Royal Society*, B, 153 (1960): 398-420.

[45]K. H. Pribram and M. M. Gill, *Freud's Project Re-Assessed* (New York: Basic Books, 1976).

[46]C. H. Waddington, *The Strategy of the Genes* (London: George Allen & Unwin, 1957).
[47]Miller et al., *Plans and the Structure of Behavior*.
[48]A. Newell, J. C. Shaw, and H. A. Simon, "Elements of a Theory of Human Problem Solving," *Psychology Review*, 65 (1958): 151-66.
[49]U. Neisser, *Cognitive Psychology* (New York: Appleton-Century-Crofts, 1967).
[50]J. R. Anderson and G. H. Bower, *Human Associative Memory* (New York: John Wiley & Sons, 1973).
[51]R. C. Schank and R. P. Abelson, *Scripts, Plans, Goals and Understanding* (Hillsdale, N. J.: Lawrence Erlbaum Associates, 1977).
[52]T. Winograd, "Framework for Understanding Discourse," *Stanford University Intelligence Monograph* (June 1977).
[53]A. M. Turing, "On Computable Numbers, with an Application to the Entscheidungs Problem," *Proceedings of the London Mathematics Society*, 2 (42 (1937): 230-65.
[54]G. M. Edelman and V. B. Mountcastle, *The Mindful Brain* (Cambridge, Mass.: MIT Press, 1978).
[55]D. H. Hubel and T. N. Wiesel, "Receptive Fields and Functional Architecture of Monkey Striate Cortex," *Journal of Physiology*, 195 (1968): 215-43.
[56]G. Werner, "The Topology of the Body Representation in the Somatic Afferent Pathway," in *The Neurosciences, vol. II*, G. C. Quarton, T. Melnechuk, and F. O. Schmitt (eds.) (New York: Rockefeller University Press, 1970): pp. 605-16.
[57]Pribram, *Languages of the Brain*.
[58]K. H. Pribram, M. Lassonde, and M. Ptito, "Intracerebral Influences on the Microstructure of Visual Cortex: I. Classification of Receptive Field Properties" (submitted to *Experimental Brain Research*).
[59]H. B. Barlow, "Single Units and Sensation: A Neuron Doctrine for Perceptual Psychology?" *Perception*, 1 (1972): 371-94.
[60]W. R. Ashby, *Design for a Brain: The Origin of Adaptive Behavior* (New York: John Wiley & Sons, 1960).
[61]K. S. Lashley, "In Search of the Engram," *Physiological Mechanisms in Animal Behavior* (New York: Academic Press, 1950), pp. 454-82.
[62]Edelman and Mountcastle, *The Mindful Brain*.
[63]Ashby, *Design for a Brain*.
[64]Miller et al., *Plans and the Structure of Behavior*; see also Pribram, *Languages of the Brain*.
[65]Miller et al., *Plans and the Structure of Behavior*.
[66]Pribram, *Languages of the Brain*.
[67]I. M. Gel'fand, V. S. Gurfinkel, H. L. Tsetlin, et al. "Some Problems in the Analysis of Movements," in *Models of the Structural-Functional Organization of Certain Biological Systems*, I. M. Gel'fand, V. S. Fomin and M. T. Tsetlin (eds.) (Cambridge, Mass.: MIT Press, 1971), pp. 329-45.
[68]M. T. Turvey, "Peripheral and Central Processes in Vision: Inferences from an Information Processing Analysis of Masking with Pattern Stimuli," *Psychology Review*, 80 (1) (1973): 1-52.
[69]Ibid.
[70]J. J. Gibson, *The Ecological Approach to Visual Perception* (Boston: Houghton Mifflin, 1979).
[71]N. Chomsky, *Language and Mind* (New York: Harcourt, Brace & Jovanovich, 1972).
[72]J. J. Gibson, *The Ecological Approach to Visual Perception* (Boston: Houghton Mifflin, 1979).
[73]I. Rock, "Perception from the Standpoint of Psychology," in *vol. XLVIII*, Association for the Research of Nervous and Mental Disease, K. H. Pribram, D. A. Hamburg, and A. J. Stunkard (eds.) (1970) pp. 1-11.
[74]J. S. Stamm and S. C. Rosen, "The Locus and Crucial Time of Implication of Prefrontal Cortex in the Delayed Response Task," in *The Psychophysiology of the Frontal Lobes*, K. H. Pribram and A. R. Luria (eds.) (New York: Academic Press, 1973) pp. 139-53.
[75]Barlow, "Single Units and Sensations."
[76]D. O. Hebb, *The Organization of Behavior: A Neuropsychological Theory* (New York: John Wiley & Sons, 1949).
[77]A. Goldscheider, "Uber die materiellen veranderungen bei der associationsbildung," *Neurologie Zentralblatt*, 25 (1906): 146.
[78]Pribram, *Languages of the Brain*.
[79]K. H. Pribram, "Some Dimensions of Remembering: Steps toward a Neuropsychological Model of Memory," in *Macromolecules and Behavior*, J. Gaito (ed.) (New York: Academic Press, 1966), pp. 165-87.
[80]K. H. Pribram, M. Nuwer, and R. Baron, "The Holographic Hypothesis of Memory Structure in Brain Function and Perception," in *Contemporary Developments in Mathematical Psychology*, R. C. Atkinson, D. H. Krantz, R. C. Luce, and P. Suppes (eds.) (San Francisco: W. H. Freeman & Co., 1974), pp. 416-67.
[81]S. S. Fox and J. H. O'Brien, "Duplication of Evoked Potential Waveform by Curve of Probability of Firing a Single Cell," *Science*, 147 (1965): 888-90.

[82]O. D. Creutzfeldt, "General Physiology of Cortical Neurons and Neuronal Information in the Visual System," in *Brain and Behavior*, M. Brazier (ed.) (Washington, D.C.: American Institute of Biological Sciences, 1961), pp. 299-358.

[83]M. Verzeano, R. C. Dill, E. Vallecaile, et al., "Evoked Responses and Neuronal Activity in the Lateral Geniculate," *Experentia*, 24 (1968): 696-8.

[84]Pribram, *Languages of the Brain.*

[85]Pribram et al., *The Holographic Hypothesis of Memory Structure.*

[86]Ibid.

[87]G. von Bekesy, *Experiments in Hearing* (New York: McGraw-Hill, 1960).

[88]G. von Bekesy, *Sensory Inhibition* (Princeton, N.J.: Princeton University Press, 1967).

[89]J. H. Dewson, III, "Cortical Responses to Patterns of Two-Point Cutaneous Stimulation," *Journal of Comparative and Physiological Psychology*, 58 (1964): 387-9.

[90]F. W. Campbell "The Transmission of Spatial Information through the Visual System," in *The Neurosciences Third Study Program*, F. O. Schmitt and F. G. Worden (eds.) (Cambridge, Mass.: MIT Press, 1974), pp. 95-103.

[91]P. H. Schiller, B. L. Finlay, and S. F. Volman, "Quantitative Studies of Single-cell Properties in Monkey Striate Cortex," *Journal of Neurophysiology*, 39 (1976): 1288-374.

[92]J. A. Movshon, I. D. Thompson, and D. J. Tolhurst, "Receptive Field Organization of Complex Cells in the Cat's Striate Cortex," *Journal of Physiology*, (1978).

[93]R. L. De Valois, D. G. Albrecht, and L. G. Thorell, "Spatial Tuning of LGN and Cortical Cells in Monkey Visual System," in *Spatial Contrast*, H. Spekreijse (ed.) (Amsterdam: Monograph Series, Royal Netherlands Academy of Sciences, 1978).

[94]D. H. Hubel and T. N. Wiesel "Receptive Field of Single Neurones in the Cat's Striate Cortex," *Journal of Physiology*, 148, (1959): 574-91.

[95]E. Roy John, *Mechanisms of Memory* (New York: Academic Press, 1967).

[96]W. R. Uttal, *Psychobiology of Emotion* (Hillsdale, N.J.: Lawrence Erlbaum Associates, 1978).

[97]J. G. Robson, "Receptive Fields: Neural Representation of the Spatial and Intensive Attributes of the Visual Image," in *Handbook of Perception, vol. V. Seeing*, E. C. Carterette (ed.) (New York: Academic Press, 1975).

[98]For reference to Ross, see E. N. Leith "White-light Holograms," *Scientific American*, 235 (4) (1976): 80.

[99]R. Bracewell, *The Fourier Transform and its Applications* (New York: McGraw-Hill, 1965).

[100]D. A. Pollen and J. H. Taylor, "The Striate Cortex and the Spatial Analysis of Visual Space," in *The Neurosciences Third Study Program*, F. O. Schmitt and F. G. Worden (eds.) (Cambridge, Mass.: MIT Press, 1974), pp. 239-47.

[101]K. H. Pribram, D. N. Spinelli, and M. C. Kamback, "Electrocortical Correlates of Stimulus Response and Reinforcement," *Science*, 157 (1967): 94-96.

[102]W. Kohler and R. Held, "The Cortical Correlate of Pattern Vision," *Science*, 110 (1949): 414-9.

[103]D. Bohm, "Quantum Theory as an Indication of a New Order in Physics." "Part A. Development of New Orders as Shown through the History of Physics," *Foundations of Physics*, 1 (4) (1971): 359-81; "Part B. Implicate and Explicate Order in Physical Law," *Foundations of Physics*, 3 (2) (1973): 139-68.

[104]Leibnitz, *Monadology and Other Philosophical Essays*, P. and A. Schrecker (trs.) (Indianapolis, Ind.: Bobbs-Merrill Co., 1965).

[105]For review of the Einstein, Podolsky, and Rosen Experiment and Bell's Theorem see B. d'Espagnat, "The Quantum Theory and Reality," *Scientific American*, 241 (1971): 158-81.

[106]K. H. Pribram, "Holonomy and Structure in the Organization of Perception," in *Images, Perception and Knowledge* J. M. Nicholas (ed.) (Dordrecht-Holland: C. Reidel, 1977) p. 4.

[107]D. Bohm, *The Special Theory of Relativity* (New York: W. A. Benjamin, 1965), p. 236.

[108]W. Heisenberg, *Physics and Philosophy* (London: George Allen & Unwin, 1959).

[109]N. Bohr, *Atomic Physics and Human Knowledge* (New York: Vintage Books, 1966).

[110]A. N. Whitehead, *Modes of Thought* (New York: Capricorn Books, 1958).

[111]K. H. Pribram, "Transcending the Mind/Brain Problem," *Zygon* 14(2) (1979): 19-30.

[112]Fritkoff Capra, *Tao of Physics* (Boulder, Colo.: Shambhala, 1975).

[113]R. Carnap, "Science and Analysis of Language," *Journal of Unified Science*, (1940): 401.

[114]H. Feigl, "Scientific Methods without Metaphysical Presuppositions," *Philosophical Studies* (1954): 406.

[115]B. Bridgeman, "Operational analysis," *Philosophy of Science* (1938): 399.

[116]B. F. Skinner, *The Behavior of Organisms* (New York: Appleton-Century-Crofts, 1938).