

The Brain

by Karl H. Pribram

"That language in which information is communicated (in the brain)... neither needs to be nor is apt to be built on the plan of those languages men use toward one another."

—Walter H. Pitts and Warren S. McCulloch*

“LOVE YOU.” It was spring in Paris, and the words had a delightful Scandinavian accent. The occasion was a UNESCO meeting on the problems of research on brain and human behavior. The fateful words were not spoken by a blonde beauty, however; they were generated by a small shiny metal device in the hands of a famous psycholinguist.

The device impressed all of us with the simplicity of its design. The loud-speaker was controlled by only two knobs. One altered an electronic circuit that simulated the tension of the vocal cords; the other regulated a circuit that simulated air puffs striking the cords.

Cells. This simple device could be relevant to man's study of himself. All behavior might be generated and controlled by an equally simple neural mechanism. Perhaps the nervous system works as a two-knob dual-process mechanism.

To understand how a dual-process mechanism could account for brain function, we must first understand the units that make up the nervous system. In the last part of the 19th Century a great controversy raged in neurobiology about whether brain tissue is made up of units—cells—as are all other tissues of the body. The controversy has been settled so conclusively that the existence of neurons—nerve cells completely separated from one another by membranes—is no longer considered theoretical. Yet, paradoxically, even

today no one has ever “seen” a neuron in brain tissue—that is, no one has traced its entire extent and shown it to be truly separate from its neighbors.

Using the spinal cord as a model, Sir Charles Sherrington was struck by the paradox that the “wire” part of neurons could not account for the complexities of reflex behavior. He proposed that the neurons were slightly separated from each other, and coined the term “synapse” for the junction between one neuron and another. He then endowed the synapse with the capability to process neural signals in such a way as to explain the reflex behavior he observed.

Barrier. Sherrington's theoretical insight has been largely ignored by neurophysiological and neurobehavioral scientists. Attention has been focused on the existence and the properties of the synapse and these have been amply documented by electron microscopy and by recordings of junctional electrical and chemical activities. But interpretation of these results has almost invariably been within the framework of the question “How does the conduction of nerve impulses pass the barrier of the synapse?” Reference restricted to cell discharge of impulses and the conducting properties of synaptic pathways is often viewed as adequate and sufficient.

Few scientists have followed Sherrington's thesis that the complexity of behavior (and of psychological proc-

*In McCulloch, *Embodiments of Mind*, 1965

Karl Pribram, a trim, soft-spoken man, relishes paradoxes. They spice his effort to understand how the brain functions. In teaching at Stanford University, Pribram often cites experimental results that cannot be explained by conventional theories. Over the years, his encounters with paradoxes produced a series of related hypotheses that eventually coalesced into a coherent theory. He describes his vision of how the brain works in his new book, *Languages of the Brain* (Prentice-Hall). In the process, he challenges many a cherished dogma. The book covers a large territory—how nerve cells communicate with each other, the role of the brain in psychological process, neural control and modification of behavior, a philosophical treatise on communication between brains and brain-mind dichotomy. This article adapts from the book Pribram's holographic theory of memory.

—DAVID POPOFF

esses) must be accounted for in terms of the complexity of organization of the junctional (synaptic) mechanisms in the central nervous system.

Following Sherrington's lead, I propose that a microstructure of junctional slow potentials is responsible for "computing" the interactions among neighboring neural elements that determine behavior and that the junctional microstructure is the key to the mystery of memory and perception.

Booster. Paradoxically, when an electrical nerve impulse reaches a synapse, it slows down and becomes so weak that a chemical booster is necessary to trigger an electrical change in an adjoining neuron. Even then, the electrical change is not a nerve impulse, but a slowly moving charge of low amplitude.

The slow, graded electrical changes generated beyond the synapse constitute, along with propagated nerve impulses, the two-process mechanism of brain function. The neural junction, rather than the neuron, is the unit around which this second powerful process is constituted.

Post-synaptic electrical and chemical events form a microstructure of electrical potentials that influences the brain tissue in which the microstructure occurs. It is these influences that can account for the modification of the brain during learning.

Growth. One of the paradoxes of memory storage by the brain is that at a person's birth his brain already contains practically all the neurons that it will ever have. Elsewhere in the body, there is growth and reproduction of tissue

throughout life—when tissue is damaged, repair takes place by division of adjacent cells. Trying to explain how memory grows during learning in the absence of neural reproduction is like trying to explain how a child could grow in the absence of the ability of the cells of his bones to divide.

In 1950 Karl Lashley—an American pioneer in brain research—reached the point of near despair after 30 years of searching unsuccessfully for engrams, memory traces in the brain. He wrote: "I sometimes feel . . . that the necessary conclusion is that learning is not possible at all. Nevertheless, in spite of such evidence against it, learning does sometimes occur."

Since Lashley made this statement, and especially in the 1960s, a great deal of anatomical and biochemical work has been done on the memory problem. I have gathered together the evidence from this and embryological research in a model of a memory storage mechanism. The model goes something like this.

Lens. Most embryological tissue is equipotential; it can develop into any body part. For example, embryonic head skin in contact with an eye vesicle forms a lens. If the eye vesicle is removed the skin will not form a lens.

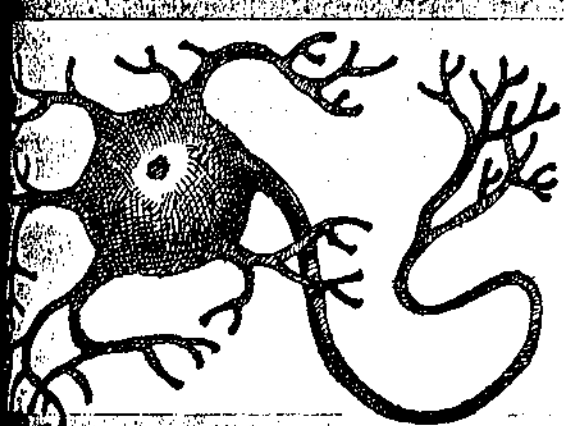
At first it was thought that the head skin already is predisposed to form a lens and that the eye vesicle simply acted as a trigger. But if the eye vesicle is transplanted to the flank, the flank skin will form a lens. And if head skin that normally forms a lens is put in contact with an ear inductor, it will form an ear; if the head skin is combined

with a nose inductor, it will form a nose.

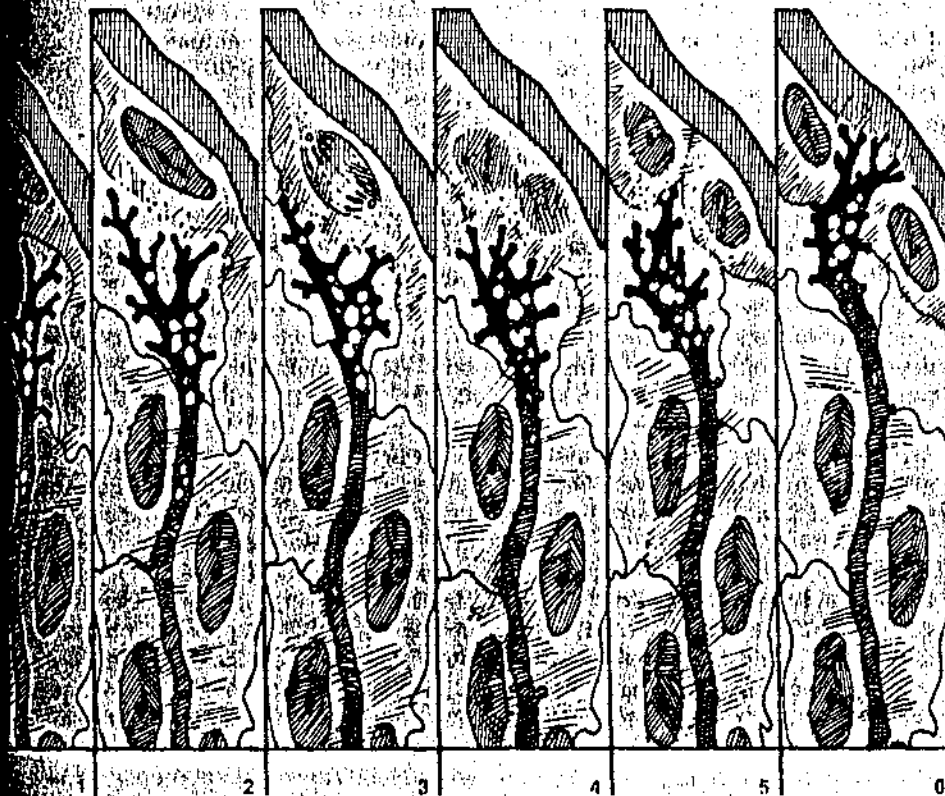
This implies that the potential to develop a myriad of structures is ordinarily repressed. A paradox is encountered, however, when biochemical analysis is made of what substances serve best to overcome this repression. The best substances are much more general in their action than would have been suspected. Endocrine secretions and an extremely interesting substance, RNA, are the best known chemical inductors. (RNA is the chemical that transcribes the inherited potential contained in DNA, the genetic memory molecule, into the proteins that compose the protoplasm of adult cells.) The paradox has not been completely resolved—either in embryology or for the memory mechanism.

Salamander. These chemicals can act on tissues from a different species, genus or even order. RNA from calf's liver can cause a lens to form in a rat's eye. And when flank skin of a frog embryo is transplanted onto the head tissue of a salamander, the resulting embryo develops a salamander head with the horny jaws and other features of a frog.

Perhaps the memory mechanism in the brain follows a similar course. A major difference, however, stems from the fact that nerve cells do not reproduce. But this does not preclude a multiplication of nerve fibers and therefore the junctions among them. That an increase in the number of neural junctions does occur when rats are exposed to an enriched environment has been demonstrated by Mark Rosenzweig and his colleagues at the University of Cali-



NERVE CELLS. Drawings of several parts of the nervous system: A) Neuron, an individual nerve cell. Brain tissue is made up of these units. B) Synapse, junction between one neuron and another. Each neuron is slightly separated from all others. C) Synapse schematic showing the chemical event in one neuron that triggers an electrical change in an adjoining neuron. Chemicals bridge the gaps between neurons.



HYPOTHETICAL NEURON GROWTH. The tips of neurons are usually enclosed in glia cells which prevent growth (1). Repeated neural activity could lead to chemical changes in the glia (2) which result in division of the glia cell (3, 4, 5). The neuron would then be free to grow beyond the daughter glia cells and make new connections (5).

fornia, Berkeley. How this increase in connectivity can occur is most readily demonstrated by peripheral nerves. However, experimental destruction of layers of cells in the brain cortex with resulting regrowth of fibers indicates that the establishment of connections is not altogether different in the peripheral and central nervous systems.

Tangle. We know that after an injury, a nerve fiber degenerates back to the cell body from which it originated. Immediately, a special type of cell already present in the sheath of the nerve begins to multiply and take up the space left by the dying fiber. These cells make a column of tissue that acts as a place-holder for the nerve fiber. Thus, when the nerve begins to regenerate, a pathway is ready for the growing tip of the nerve fiber to follow. When the tissue column is not present, the nerve's growth cone pushes off in every direction and forms a nonfunctional tangle that is often painfully sensitive.

Similar place-holding cells, called glia or neuroglia form a sheath for neurons in the central nervous system. These glia ordinarily encase the tip of nerve fibers and preclude growth.

There is now good evidence obtained by Holger Hydén in Göteborg, Sweden, that when a nerve impulse reaches a synapse, it triggers the production of specific RNA molecules. Just as in embryonic tissue, RNA induces (or at least is correlated with) marked metabolic activity in the glial cells that envelop the neurons. The repetition of the nerve impulse pattern could cause the glial cells to divide, thus leaving the tips of neurons free to grow be-

The brain may be the originating power of the perceptions of hearing and sight and smell, and memory and opinion may come from them, and science may be based on memory and opinion.

—PLATO (c. 427-347 B.C.)

The brain in all animals is bloodless, devoid of veins, and naturally cold to the touch. . . .

From the eye there go three ducts to the brain. . . . nature has contrived the brain as a counterpoise to the region of the heart with its contained heat. . . . The brain, then, tempers the heat and seething of the heart. . . . Of all animals, man has the largest brain in proportion to his size; and it is larger in men than in women. This is because the region of the heart and of the lung is hotter and richer in blood in man than in any other animal; and in men than in women.

—ARISTOTLE (384-322 B.C.)

To imagine that the brain was created because of the natural heat of the heart, to refresh it and moderate its temperature, is wholly absurd. . . .

Under all conditions one finds the brain to be much warmer than the air. . . . But it is not yet realized by all that the brain is the beginning of the nerves, just as it is of the spinal cord; and that some of them originate from the brain itself, others from the spinal cord; . . . and yet in dissections the fact is thus.

—GALEN OF PEGASUS (A.D. 128-199)

tween the daughter glial cells to make new contacts with neurons beyond.

This is one way that the junctional microstructure with its electrical and chemical characteristics can become modified by experience. Once this has occurred, of course, subsequent behavior is determined by the modification of brain tissue.

Storage. Let us now change pace and turn to a specific memory process—recognition—for additional insights into the properties of the brain's memory store.

First, it is obvious that recognition depends on memory storage. What is not so obvious is that most perception is based on the state of current neural organization, the current brain state. A considerable part, though by no means all, of this organization is built into the brain. How much experience modifies what we perceive is evident from experimental results obtained a decade ago by Eugene Sokolov at the Moscow State University.

Sokolov performed a simple demonstration that uncovered one of those fruitful paradoxes that guide experimentation in the neurobehavioral sciences. When a person is exposed to the beep of a horn, he ordinarily starts and turns toward it. But should the horn beep be repeated frequently, his reactions diminish markedly. The subject is said to be habituated to the stimulus.

This lack of reaction to the continuing beep turns out to be deceptive, however. Actually a great deal is still going on. For if the stimulus changes slightly, the beep becomes new to him, and he reacts accordingly.

reactions recur. This is the paradox. Until Sokolov's demonstration, psychologists and physiologists assumed that habituation simply made the nervous system less sensitive to input. But Sokolov's findings indicate that the person who has habituated must be matching the present sound against a stored representation of prior tone beeps.

Habituation thus does not indicate loss of sensitivity by the nervous system; it shows that the brain develops a neural model of the environment, a representation, an expectancy against which inputs are constantly matched.

Neurosurgeons and neurophysiologists have in their own way demonstrated that a brain state needs to be organized before perception occurs. They have explored the surface of living human brains using mild electrical stimulation. When the electrical probe touches the brain in some locations it produces movements of parts of the body (on the side opposite to that stimulated) or in other locations, sensations of body parts. Benjamin Libet of the University of California Medical Center in San Francisco recently has shown, however, that the awareness produced by stimulation is not immediate. It takes from half a second to five seconds before the person has an experience to report. It thus appears that electrical stimulation gradually organizes a state in the brain tissue, and only when the brain reaches that state does the person become aware. The nerve impulses generated by the electrical stimulation are not in and of themselves available to immediate awareness. Only when the neural organization, the brain state, that is coordinate with perceptual awareness?

Donald Hebb of McGill University reviewed the problems involved in understanding the neural organization of perception—especially of the recognition process—incisively in his classic volume *The Organization of Behavior*. He states: "One must decide whether perception is to depend 1) on the excitation of *specific cells* or 2) on a *pattern of excitation* whose locus is unimportant." Hebb makes his choice: "A particular perception depends on the excitation of particular cells at some point in the central nervous system."

Research during the past decade appears to have vindicated his choice. Microelectrode studies such as those of David Hubel and Torsten Wiesel at Harvard University have identified neural units that respond to one distinctive feature of visual pattern, such as direction of movement, tilt of line, etc. Today, the body of neurophysiological opinion would agree, I believe, with Hebb that one percept corresponds to one neural unit.

D.C. However, it seems to me that Hebb's choice may be a Hobson's choice. When Hebb wrote his book there were two general views of how the nervous system might operate. The well-substantiated view dealt with the generation of nerve impulses and their transmission across connections between nerves. The other view dealt with fields of electrical potentials. Wolfgang Köhler of Swarthmore College based his Gestalt arguments on these non-neuronal fields and was not so prone to their physiological existence (Coffman, p. 122, 1961).

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Next, as organs, the faculty of Imagination had, first, the front lobes of the brain and the psychic spirits contained in them, then the nerves impregnated with psychic spirits that proceed from them, and, finally, the whole construction of the sense-organs. These organs of sense are five in number, but perception is one, and is an attribute of the soul. By means of the sense-organs, and their power of feeling, the soul takes knowledge of what goes on in them. . . .

The organ of the faculty of Intellect is the middle part of the brain and the vital spirit there contained.

—ARISTOTLE OF STAGIRA (B. C. A. D. 384)

One of the animal internal faculties of perception is the faculty of fantasy, i.e., *sensus communis*, located in the forepart of the front ventricle of the brain. It receives all the forms which are imprinted on the five senses and transmitted to it from them. Next is the faculty of representation located in the rear part of the front ventricle of the brain, which preserves what the *sensus communis* has received from the individual five senses even in the absence of the sensed objects.

—ARISTOTLE (A. D. 800-1037)

—That very subtle fluid, called animal spirit . . . constantly flowing from the heart through the brain into the muscles, is the cause of all movements of our parts.

Consider that the little threads that come from the most interior part of the brain and compose the marrow of its nerves, are so disposed in all those parts that serve as sensory organs, that they can very easily be moved by the objects of these senses; and that when they are moved there, even slightly, in the same instant they pull upon the parts of the brain whither they come, and in the same way, upon the entrances of certain pores that are in the interior surface of the brain, by which the animal spirits in its cavity immediately begin to flow and travel by the pores into the nerves, thence into the muscles which, in this machine, serve to produce movements very similar to those to which we are naturally endowed when our senses have been touched in the same way.

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In the decade after Hebb published his statement.

I was fortunate to be able to take part in these explorations. The experimental attacks were successful. Direct-current electrical fields were found to be generated in appropriate regions of the brain when the senses were stimulated. And by applying an electrical current of appropriate polarity directly to the brain, they could retard or speed perceptual learning.

But when Köhler insisted that the electrical fields were the basis for perception, I remained unconvinced. Lashley had placed gold foil over the surface of cats' brains in an attempt to short-circuit electric fields and found that this did not disrupt perception. Roger Sperry of the California Institute of Technology had cross-hatched areas of the cortex and inserted mica-strip insulators in an attempt to alter the configuration of electrical fields. This also failed to alter perception. Köhler felt that these procedures were inadequate to the purpose for which they had been undertaken and that the experiments did not prove what they were meant to prove.

But when I made multiple applications or injections of aluminum hydroxide cream onto or into the cortical surface and markedly and demonstrably disrupted the brain's electrical activity without impairing pattern discrimination, Köhler exclaimed: "That ruins not only my field theory but every other current theory of perception."

Stroke. Why was Köhler so dismayed by these results? On the basis of many experiments that detailed interactions

among the effects of neighboring sensory stimulations he came to the conclusion that nerve impulses per se, being discrete in time and place, could not account for perceptual phenomena. But it was again Lashley who made the case imperative for "field" theories of brain function even though he did not agree with Köhler's particular formulation. Lashley performed experiments with rats to show that, paradoxically, even very large destructions of brain tissue fail to impair recognition. These experiments bore out a common clinical observation: a man who has a stroke that destroys half or more of his visual system does not thereafter fail to recognize half his family. The organization of the brain's memory store is such that particular memories are hard to wipe out. The information in memory appears to be distributed over large areas in the brain.

In his search for a hypothesis to explain how nerve impulses transmitted over discrete paths could be converted into a general field of activity that functioned independently of particular nerve cells, Lashley suggested that an interference-pattern model would account for the phenomena. But having nothing but nerve impulses to work with, he was unable to specify a mechanism satisfactory even to himself and he never pursued his insight.

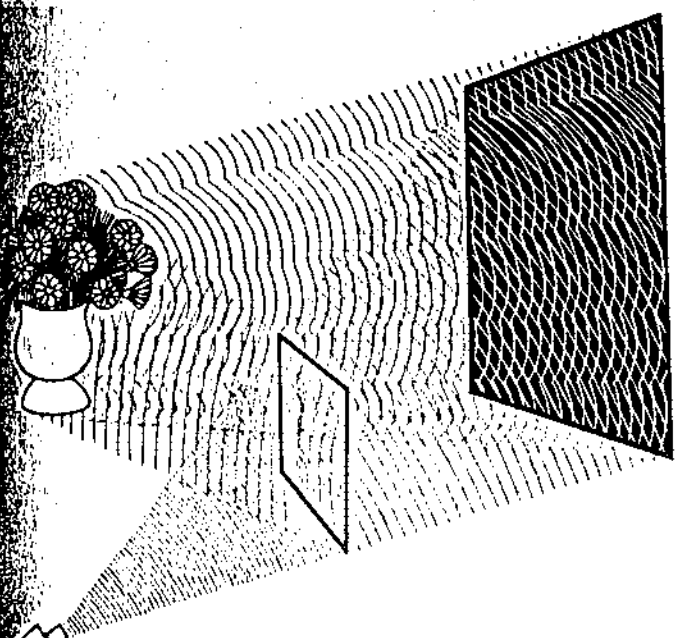
Holograph. The two-process mechanism of brain function with its emphasis on a microstructure of junctional slow potentials provides a plausible realization of the interference pattern hypothesis. Further, a specific physical model of the interference process has

become available in the past two decades with the advent of holography. This physical model elegantly demonstrates the properties of brain organization in perception such as neighborhood interaction and distributed information so dear to psychologists concerned with Gestalt phenomena.

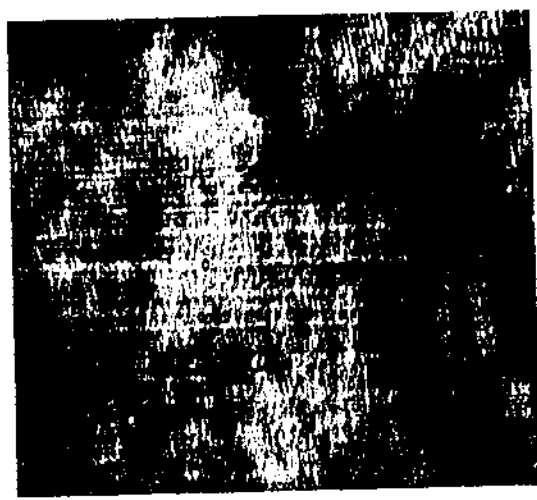
Holography is a kind of photography or in more sophisticated terminology an optical information-processing mechanism. But holography differs radically from normal photography. In a regular camera the film records the intensity of light that is reflected from objects. Each point on the film stores information from a single corresponding point in the photographed scene. The resulting picture looks like the original scene. In holography light from every point in the scene is distributed (diffused) to many points in the film. When the film is developed, no visible pictures or images appear; instead the film has a pattern of tiny and larger swirls, interference patterns that look like a piece of moiré silk.

Film. To create a hologram, coherent light (from a laser, for instance) is divided and part goes directly to a photographic film and part is reflected from an object or scene and then converged onto the film. At the film the two beams of light interact to form interference patterns. The film records these interference patterns.

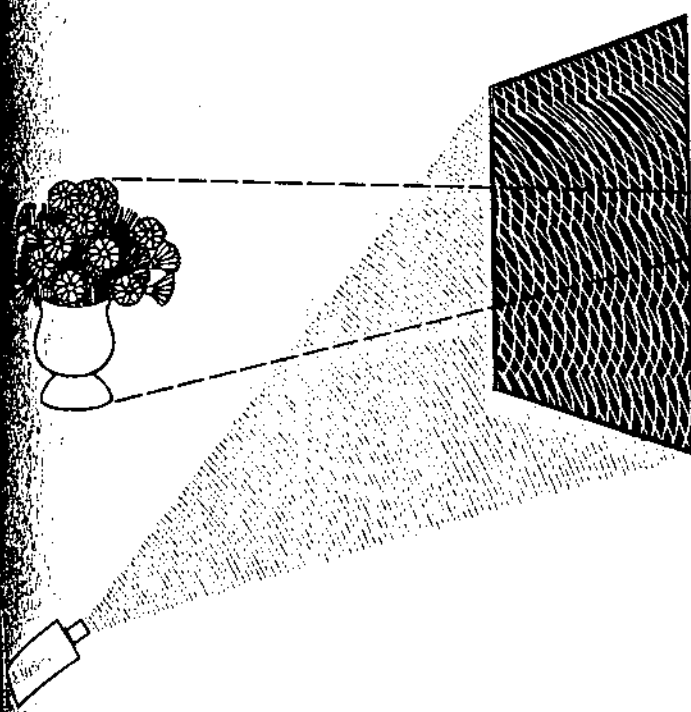
To recreate the scene, the hologram has only to be illuminated by a reasonably coherent light. Or, alternatively, if the hologram has been constructed initially by directing both beams at objects using each as a reference for the



MAKING A HOLOGRAM. A laser beam is split, part of the light directed to a photographic plate and the other part reflected from an object to the plate.



ENLARGED HOLOGRAPHIC PLATE. Result of interference patterns from object and from reference beam.



RECONSTRUCTING THE HOLOGRAM.



Light from the reconstruction beam is diffused by the plate in the same way light from the object was diffused by the plate.

other, then both objects can be "imaged" when only one is re-illuminated. Holograms thus possess the property of associative recall. We have all experienced the phenomenon of revisiting an old neighborhood after many years and suddenly remembering shops and doorways and even placements of furniture in the apartment we lived in. Had we been asked to recall these memories without the input from the "reference" objects, the streets and buildings of the neighborhood, we would have been unable to do so.

Further, the image from a hologram has true three-dimensional perspective. By moving his head, a viewer can look around and behind objects in the picture, just as if he were looking at a real scene from different positions.

Fragment. But as a model for brain function in perception, most pertinent is the ease with which information becomes distributed and retrieved in holography. The holographic film can be cut into fragments and each fragment when it is illuminated, will produce the entire image. Damage to any part of the film—even a large part—will not visibly degrade the image reconstructed from the remainder. Tear an ordinary photograph of your family in half and half the family disappears. Do this to a hologram and recognition remains unimpaired.

In addition, the hologram has a fantastic capability to retrievably store information. Many different interference patterns can be super-imposed in one hologram. Some 10 billion bits of information have been stored holographically in one cubic centimeter! Dis-

tributed information and the incredibly large storage capacity—two properties of the brain mechanism in recognition—are thus accounted for by the model.

Systems. Holography does not depend on the physical presence of light waves even though the mathematical equations that describe holograms are derived from wave mechanics. Computer simulation of the holographic process has been achieved and promises to be an important aid to present-day information-processing systems.

This independence of holography from actual physical wave production is important to understanding the neural holographic process since there is considerable doubt whether brain waves such as those recorded by the electroencephalograph (EEG) could be the basis of holographic information processing, although they may indicate that such a process is taking place. The amount of information storage is an inverse function of wave length and ordinary brain waves are rather long.

Arrival. But the junctional microstructure of slow potentials provides the rich substrate demanded by a holographic process. Consider the arrival of neural impulses at a set of synapses. When the arrivals converge from at least two sources, they create interference patterns. Such patterns have been demonstrated to occur in the cerebellar cortex and therefore are most likely in other cortical tissue.

Experiments by Fergus Campbell and his associates at Cambridge University have provided some direct support for a neural holographic process. Campbell used differently spaced diffraction gratings and showed that visual potentials evoked by a grating with one spacing will be habituated to a range of spacings. This indicates that the brain mechanism involved is sensitive not to the spacing per se, but to a transformation that encompasses the range of gratings. Such a transformation is mathematically identical to those that are used to make holograms. Campbell's experimental result accounts for the fact that a child who has learned to identify the letters of the alphabet by sight can recognize them no matter what size they are. The child readily identifies a 20-foot letter "A" on a billboard even if all the A's he has seen before then have been a quarter of an inch in height.

Angle. Just recently these experiments have been taken a step further by

David Pollen at Harvard University. Pollen has shown that "the striate cortex transforms the topographic representation of visual space in the lateral geniculate body into a Fourier transform or spatial frequency representation at the complex cell level via the intermediary simple cell [line sensitive] stage of 'strip integration.'" In short, the brightness distribution falling on adjacent reactive fields is "effectively decomposed into a set of sine wave gratings at all possible position angles and covering a wide range of cycles per degree of visual angle" fulfilling Campbell's experiment promise.

If recognition is a holographic process, then the visual system separates the perceived spatial frequencies of an object into independent channels and uses the ratio of these frequencies—the interference pattern—to identify the object. In such a process, the relative harmonic content would be sorted in the memory system, making the absolute size of the object irrelevant. If every size of every object had to be filed in the memory system, both storage and retrieval would be complicated.

The study of visual perception in infants also supports the holographic hypothesis. Contrary to the widely held views based on Hebb's theories, size-and-shape constancy do *not* emerge from a combination of prior and presumably more primitive perceptions. Hebb's suggestion was based on experiments and clinical observations in which subjects were reared under conditions of sensory deprivation. He assumed that experience was necessary for the proper development of brain function in perception. But experiments by Thomas Bower at Harvard University have shown that six-week-old infants already display size and shape constancy and that these constancy phenomena are dependent on parallax (seeing one object move in front of another). What simpler mechanism for sensitivity to parallax exists than the three-dimensional perspective provided by holography?

Eye. Electrophysiological experiments by Hubel and Wiesel have also shown that the mechanisms for feature detection are already well developed in the brains of mammals at birth and that they deteriorate as a consequence of sensory deprivation. Further, when deprivation is limited to one eye the electrophysiological deterioration is much greater than when both eyes are deprived despite the fact that each cor-

tical feature detector is connected to both eyes. Thus, sensory deprivation does not affect the development of feature detector function. Either the mechanism atrophies through lack of use or the malfunction induced by deprivation actively suppresses it. In either case, the mechanism involves the connectivity among detectors, their junctions, not the detector neurons themselves. And as we have already seen, there is ample evidence that the junctional microstructure is highly sensitive to modification by experience.

Mode. My account of perception has been one-sided. I have singled out the visual mode and analyzed only one aspect of it. The holographic hypothesis, with modifications, must hold for other sensory modes if it is to be generally useful.

The models of the auditory and sense of touch processes proposed by Georg von Békésy of the University of Hawaii use identical equations to those that describe the holographic process. Application of the holographic hypothesis to studies of auditory and somato-sensory brain processes, therefore, should be both feasible and rewarding.

As yet, too little is known about the neurological processes of taste and smell to allow more than a guess that the holographic model may be applicable. But again Békésy has shown how this might be done, and unit analysis of neurons in the olfactory bulb by Jerome Lettvin of the Massachusetts Institute of Technology suggests that the approach is reasonable.

When the holographic model is taken seriously, many paradoxes regarding brain function in perception become understandable. This does not mean that all brain function can be reduced to a holographic process, or that all the problems of recognition yield to holographic analysis.

The neural hologram is used to explain the psychological function of perception and the distributed memory mechanism in the brain. It does not follow that memory is distributed helterskelter all over the brain—and memory mechanisms other than those that fit the holographic model must play a role—even in perception and certainly in recognition.

The outlines of the neural holographic process are only now coming into focus—yet at least outlines are before us—where not so long ago, only vague hobbits inhabited the land of neuro-mythology.