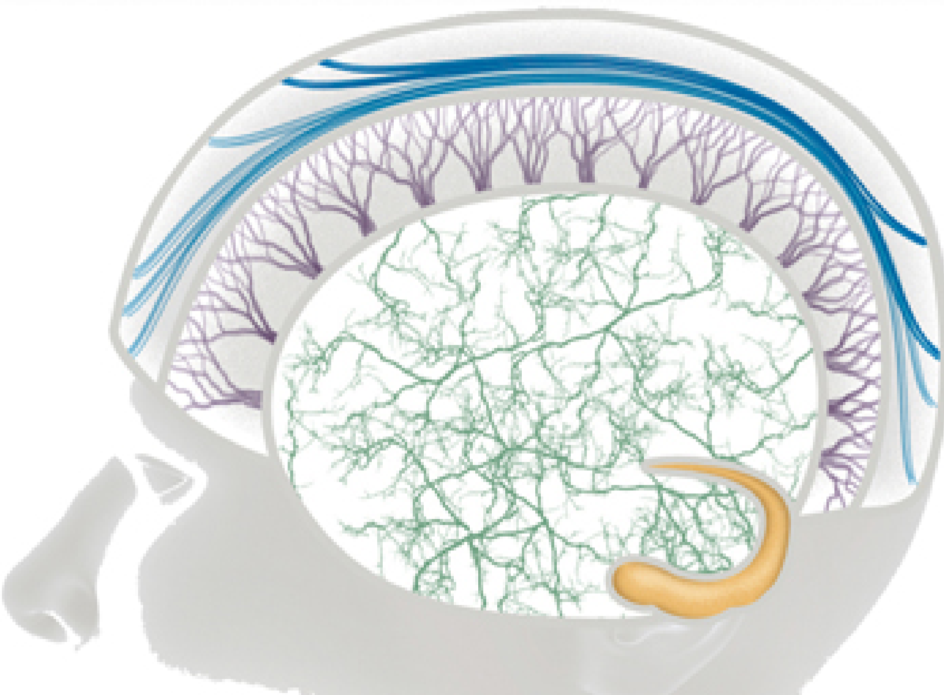
# THE FORM WITHIN

## MY POINT OF VIEW



KARL H. PRIBRAM, MD

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KARL H. PRIBRAM,
MD, PhD (Hon. Multi)

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*The Academy is particularly proud to award the seal to Dr. Karl Pribram who, in 2010, received the Academy's award for his Distinguished Career in Science.*

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# Prologue

## The Quest

*When Clerk-Maxwell was a child it is written that he had a mania for having everything explained to him, and that when people put him off with vague verbal accounts of any phenomenon he would interrupt them impatiently by saying, 'Yes; but I want to know the particular go of it!' Had the question been about truth, only a pragmatist could have told him the particular go of it. . . . Truths emerge from facts; but they dip forward into facts again and add to them; which facts again create or reveal new truth. . . . And so on indefinitely. The facts themselves are not true. They simply are. Truth is the function of beliefs that start and terminate among them.*

—William James, *Pragmatism: A New Name for Some Old Ways of Thinking,* 1931

Have you noticed the massive interest shown by the scientific community in studies of mind and brain? *Scientific American* is publishing a new journal, *Mind*; *Psychology Today* is headlining studies of the workings of the brain; *Popular Science* and *Discover* are filled with tales of new discoveries that relate mind to brain and 37,000 neuroscientists are working diligently to make these discoveries possible.

It has not always been this way. When, as an undergraduate at the University of Chicago in the 1930s, I took a course on the nervous system, we stopped short of the brain cortex—and what we now know as the "limbic systems" was dismissed as a most mysterious territory called the "olfactory brain."

It was this very lack of knowledge that attracted me: *The Form Within* is the story of my adventures in charting this most important world about which we then knew so little. In the process, the data I gathered and the colleagues with whom I worked changed what opinions I had brought to the research and added sophistication to my interpretations. In retrospect what impresses me—and what I urge my students to appreciate—is the long time required, sometimes decades of passion, persistence and patience, for an idea to ripen into a body of hard evidence and a theoretical formulation that I was finally able to communicate clearly to others.

*The Form Within* tells the story of my voyage of discovery during almost a century of research and theory construction. The story is set within the frame of the discoveries of the previous century, the 19th, which totally revised our understanding in the Western world of how our brains work. During the 17th century and earlier, the human brain was thought to process air, often termed "spirits." With the advent of the sciences of chemistry and of electricity, a basic understanding of brain processes was attained that, to a large extent, resembles our current views. Writings like those of William James and Sigmund Freud, around the juncture of the two centuries, will be referenced repeatedly in the following chapters.

My own story has a somewhat different perspective from that which is currently available in most neuro- and psychological science books and journals. For example, my interactions with the 20th century "shapers of viewpoints" in the brain and behavioral sciences—B.F. Skinner and Karl Lashley, experimental psychologists; Wilder Penfield, neurosurgeon; Arthur Koestler, author; John Eccles, neurophysiologist and Karl Popper, philosopher—expose the questions that puzzled us rather than the dogma that has become associated with their names.

Thus, *The Form Within* is the story of my quest. It charts a voyage of discovery through 70 years of breakthroughs in brain and psychological research. More than a hundred students have obtained their doctoral and postdoctoral training in my laboratory and gone on to productive and in some cases outstanding careers. Collaboration with scientists on five continents has formed and continues to form my views. The voyage is not over: each month I've had to add to, and in some cases revise, this manuscript. But as a work in progress, *The Form Within* is to me an inspiring chronicle of a most exciting voyage through what, often, at the time, has seemed to be a storm of experimental and theoretical findings. As you will see, the concept of form—*the form within* as formative causation—provides a novel and safe vessel for this journey.

# Preface

## The Form Within

*The first thing we have to say respecting what are called new views . . . is that they are not new, but the very oldest of thoughts cast into the mold of these new times.*

—Ralph Waldo Emerson, "The Transcendentalist," 1842

A major thrust in our current changing view of humanity has been our growing understanding of what our brain does and how it does it. As always, in times of change, controversies have arisen. Not surprisingly, some of the most exciting findings, and the theories that are derived from them, are being swept under the rug. In *The Form Within* I have enjoyed placing these controversies within the larger context of complexity theory, framed by two ways of doing science from the time of classical Greece to the present. Within such a frame I bring to light findings that deserve our attention which are being ignored, and I clarify the reasons why they are being ignored.

Critical to any communication of our brain's complex inner activity and its interaction with the world we navigate is the concept of "form": *The Form Within*. We are in the midst of an in-form-ation revolution, begun in the latter half of the 20th century, that is superseding the Industrial Revolution of the 19th and early 20th centuries. The Industrial Revolution had created a vast upheaval through the impact of changes that occurred in our *material* world. The information revolution that is now under way is changing the very *form*, the patterns of how we navigate that world.

*This revolution has many of the earmarks of the Copernican revolution of earlier times. That revolution inaugurated a series of scientific breakthroughs such as those by Galileo, Newton, Darwin and Freud. Though often unintended, all of these and related contributions shifted humans from center stage to ever more peripheral players in the scientific scenario.*

*The current information revolution redresses and reverses this shift: Once again science is showing that we humans must be perceived as the agents of our perceptions, the caretakers of the garden that is our earth, and how we can be actively responsible for our fellow humans. As during the Copernican revolution, the articulation of new insights is halting, often labored, and subject to revision and clarification. But the revolution is under way, and the brain and psychological sciences are playing a central role in its formulation. This orientation toward the future is what has made* The Form Within *so interesting to write.*

*This frame provides the form in which we communicate scientific research and theory. Form is the central theme of this book. Form is defined in Webster's dictionary as "the essential nature of a thing as* *distinguished from its matter." What has been lacking in the brain sciences is a science-based alternative to matter-ialism. Form provides such an alternative.*

The dictionary continues its definition. "Form" forms two currents: form as *shape* and form as *pattern*. Twentieth-century brain scientists felt comfortable in their explanations using descriptions of shape but less so with descriptions of pattern. Matter has shape. Most brain scientists are materialists. By contrast, communication by way of the transmission of information is constituted of pattern. Despite paying lip service to describing brain function in terms of information processing, few classrooms and textbooks make attempts to define brain processing in the strict sense of *measures of information* as they are used in the communication and computational sciences. A shift from the materialism (explanations in terms of matter) of the Industrial Revolution of the $19^{th}$ and early $20^{th}$ centuries, to this "form-al" understanding of *in-form-ation as pattern* is heralding the Communications Revolution today.

But measures of information per se are not enough to convey the impressions and expressions by which we think and communicate. When the man in the street speaks of information, he is concerned with the meaning of the information. Meaning is formed by the context, the social, historical and material context within which we process the information. Thus, in *The Form Within* I address meaning as well as information.

The distinction between form as shape and form as pattern has many ramifications that make up the substance of the arguments and explanations I will explore throughout this book. For instance, as Descartes was declaring that there was a difference between "thinking" (as pattern) and "matter" (as shape), he was also providing us the way to *trans-form* shape and pattern by bringing them together within co-ordinates—what we know today as "Cartesian coordinates."

The resolution of our question "what does the brain do and how does it do it" rests on our ability to discern, in specific instances, the transformations, the changes in coordinates, that relate our brain to its sensory and motor systems and the ways in which different systems within the brain relate to each another. *The Form Within* gives an account of many of these *transformations,* especially those that help give meaning to the way we navigate our world.

# The Cortical Primate

Toward the end of the Last Ice Age—about 10,000 years ago—a new breed of primates began to leave its mark on Earth. These creatures possessed a large brain cortex that allowed them to refine—that is, to fine-tune—their experience by reflecting and acting upon it.

In the autumn of 1998, Katherine Neville and I were granted rare private invitations to visit the prehistoric painted caves at Altamira, in Spain. We arrived on a cold, blustery day, and we were happy to enter the shelter of the ancient caves. Despite the many photos we had seen, nothing prepared us for the power of these images, hand colored more than 12,000 years ago. I immediately recalled my colleagues' attempts to get chimpanzees (who can do so many other things very well) to make paintings. The difference between the crude swishes that the chimpanzees lobbed onto flat surfaces and these detailed figures of gazelles and oxen that adorned the rough stone walls and ceilings in the caves revealed, in a few seconds, the difference between us humans and other creatures. By what process had swipes of ochre been refined into such exquisite painting?

*1. Altamira cave painting*

What also impressed me was the location of the paintings: Today the floor where we walked is hollowed out, but when the paintings were made, the ceiling was so low that no one could stand erect. During prehistoric times, the painters must have lain on their backs in this restricting passage. Anyone who has tried to cover a ceiling using a paintbrush has experienced the aches that go along with doing something from an unnatural position. And by what light were the paintings executed? There is no evidence in the caves of smoke from torches. How, in that ancient time, did the artists illuminate those caves? Just how and to what purpose did *they* re-form the world of their caves?

Early human beings refined and diversified—*formed* —their actions to *re-form* their world with painting and song. Storytellers began to give diverse meanings to these diverse refinements by *formulating* legends and myths. In turn, their stories became accepted as constraints on behavior such as laws (modes of conduct) and religious injunctions (from Latin, *religare,* "to bind together, to tie up"). Today we subsume these forms of cultural and social knowing and acting under the heading "the humanities."

Along with stories, early human beings began to *formulate records* of diverse observations of recurring events that shaped their lives: the daily cycle of light and darkness as related to the appearance and disappearance of the sun; the seasonal changes in weather associated with flooding and depletion of rivers; the movements of the stars across the heavens and the more rapid movements conjoining some of them (the planets) against the background of others; the tides and their relationship to the phases of the moon—and these to the patterns of menstrual cycles. Such records made it possible to anticipate such events, and subsequently to check these anticipations during the next cycle of those recurring events. Formulating anticipation of their occurrence gave meaning to our observations; that is, they formed predictable patterns. Today we subsume these patterns, these forms of knowing about and acting on the world we navigate, under the heading "the sciences."

There has been considerable dissatisfaction among humanists with the materialist approach taken by scientists to understanding our human condition. What has been lacking is a *science-based* alternative to materialism. Form as "the essential nature" of our concerns provides us such an alternative.

## Form as Shape and Form as Pattern

Both form as shape and form as pattern have roots in early Greek mathematics. Today we associate form as shape with the name Euclid, who wrote the first known axiomatic theory (a theory based on a few assumptions from which propositions are logically deduced). Euclid's assumptions were devoted to geometry. We were taught Euclid's geometry in high school and we are thus familiar with it. *In geometry (that is, earth-metrics) we measure—in the British system—what is in our Yards as we pace them with our Feet, or in the case of the height of horses, with our Hands. Geometry is a hands-on way of out-lining shapes. In Euclid's geometry, parallel lines do not meet.*

By contrast, *form as pattern* is today associated with the name Pythagoras. Pythagoras is an elusive figure who is known principally through the writings of the "school" he founded. We are currently acquainted with Pythagoras through trigonometry, the study of tri-angles that are archetypes, "forms or patterns from which something develops." The term "archetypes" is derived from *tepos*, "tapping." Pythagoras noted that tapping pieces of metal of different sizes gave rise to different sounds. He later noticed that, in a similar fashion, tapping taut strings of different lengths gave rise to oscillations in the string that appeared as waves. Different sounds were produced by strings of different lengths. A string divided in two gives rise to sounds an octave higher than the original. Measurement of the length of strings that give rise to different sounds could be ordered, that is given ciphers or numbers. From the archetype of waving strings, music was derived.

The cyclic oscillations of the strings that appear as waves vary in frequency (density) according to the length

of the oscillating strings. An insight that seems ordinary to us but has had to be repeatedly achieved anew is that the wave-forms can also be represented by a circle: perhaps noted by the Pythagoreans as the form taken by sand spread lightly on the surface of a drum. Achieving this seminal insight will be encountered on several occasions in the chapters of *The Form Within*. But we come across it first with Pythagoras.

Thus, once the circle form is recognized, numbers can be assigned to different parts of the circle. Pythagoras did this by forming a tri-angle within the circle, a triangle one of whose angles rests on a point on the circle. Arranging the numbers within a cycle as a circle allowed Pythagoras to tri-angulate (as in trigonometry) a location on the circle and describe the location by its *angles* (by way of their sine and cosine). *These angles could measure contexts beyond those that we can lay our hands on: Go to the nearest railroad track— the tracks do not obey the Euclidean* *postulate that parallel lines do not meet. Rather the tracks appear to meet at an angle near the horizon which forms a circle.*

Pythagoras had therefore two number systems available: the frequency or density of the wave-forms and the numbers forming each cycle.

Note again that geometry develops an active, *out-lining* method of measurement that is *limited in the range being investigated*. By contrast, relationships among numbers engage an *in-formative*, an imaginative and inventive *proactive* procedure (as in trying to assess the meaning of the apparent convergence of railroad tracks at our horizon). Form as shape and form as pattern have led to two very different ways of guiding our approach to the world we navigate.

In the succeeding chapters of *The Form Within*, I describe a newer, still different type of formulation: proactive, dynamical "self-organizing" processes that occur in our brains and lead to progressively refining our observations, and thus to refining the targets of our actions and the diversity of our perceptions. This is the very essence of *both* the humanities and the sciences.

Sounds forbidding? It is. But accompany me on this fascinating and amazing journey and you may be surprised at how comprehensible the many facets of this three-pound universe have become today. And how an intimate knowledge of your brain will affect the way you transform *your* world.

## The Story

Most of *The Form Within* is organized according to topics and issues of general interest as viewed from the vantage of those of us working within the sciences of brain, behavior and mind. However, in the first three chapters, I address issues such as how to proceed in mapping correlations, a topic totally ignored in the current surge in using fMRI to localize the relations between brain and behavior; how I came to use metaphors and models, which is just coming into focus in doing experiments in psychology; and how I came to describe self-organizing processes in the fine-fiber webs and the circuitry of the brain.

The main body of the text begins with the topic of perception. Of special interest is the fact that, contrary to accepted views, the brain does not process two-dimensional visual perceptions; rather, the brain handles many more dimensions of perceptual input. This conclusion is reached because I make a distinction between the functions of the optic array and those of retinal processing. Furthermore, evidence shows that there is as much significant input from the brain cortex to the receptors as there is input from the environment.

In a subsequent chapter, I present evidence to show that the brain's control of action is by way of "images of achievement," not just motor programs—and the resultant support of the currently dismissed "motor theory" of language acquisition.

And there is more: The neural processing of pleasure, which accounts for the intertwining of pain- and temperature-transmitting fibers in the spinal cord, is shown to be straightforward; so is the evidence for how brain processes are involved in setting values and making choices, as well as how brain processes compose, through interleaving cognitive with emotional/motivational processes, the formation of attitudes.

Finally, a series of chapters is devoted to new views on encompassing issues such as evolution, memory, consciousness, mind/brain transactions, and the relation between information processing and meaning. These chapters challenge, by presenting alternatives, the prevailing views presented by philosophers of science, especially those concerning the relation between brain and mind. Much of what composes these and other chapters of *The Form Within* cannot be readily found in other sources.

The first three chapters that follow this preface are organized, somewhat in the order that I utilized them, according to three different types of procedure that I used to study what the brain does and how it does it: 1) Correlations, 2) Metaphors and Models, and 3) The Biological Imperative.

By correlations I mean discoveries of relationships within the same context, the same frame of reference (the same coordinate systems.) We humans, and our brains, are superb at discovering correlations, sometimes even when they are questionable. Such discoveries have abounded during the two past decades, by way of PET and fMRI image processors, techniques that have provided a tremendous surge of activity in our ability to make correlations between our brain, behavioral and mental processes. But correlations do not explain the processes, the causes and effects that result in the correlations.

Metaphors and models, by contrast, are powerful tools that we can use to guide our explorations of process. We can model a brain process that we are exploring by doing research on a device, or with a formulation that serves as a metaphor, and we can then test in actual brain research whether the process that has been modeled actually works. *The Form Within* uses telephone communications, computer programs, and optical-engineered holographic processes wherever relevant. For the most part our metaphors in the brain/behavior/mind sciences come from engineering and mathematics.

Brain and behavioral research (such as that obtained through correlation and the use of metaphors) often develops questions that lead directly to brain physiological research. My research led to understanding a biological imperative: the self-organizing property of complex processing.

In subsequent chapters of *The Form Within*—the topic-oriented chapters—I have noted the results of the application of the insights obtained as they become relevant.

## In Summary

1. The Prologue and Preface of *The Form Within* have stressed that we are experiencing a period of revolution in science akin to that which shaped our views during the Copernican revolution. We humans are reasserting the centrality of our viewpoints and our responsibility toward the environment within which we are housed.
2. This reassessment of our centrality can be formulated in terms of a neglect of a science based on pattern that has resulted in a science based on matter, an overarching materialism.
3. Form deals with the essence of what is being observed, not only its matter. Form comes in two flavors: form as shape and form as pattern.
4. Current science, especially the brain and behavioral sciences, has been comfortable with explanations in terms of form as the shapes of matter. But contemporary science is only rarely concerned with form as patterns.
5. The distinction between form as shape and form as pattern is already apparent in Greek philosophy. Euclid's geometry, as taught in our

high schools, uses descriptions of form as shapes. Pythagoreans have dealt with patterns of numbers that describe wave-forms, angles and circles, as in tonal scales and in trigonometry.

6. In *The Form Within*, when appropriate, I trace these two different formulations of research and theory development in the brain/behavior/experience sciences.
7. Within this context, I develop the theme that the brain/behavior/mind relationship receives a major new explanatory thrust based on the observed biological imperative toward self-organization.

# Formulations

# Chapter 1
## Correlations

Wherein I explore the shapes and patterns that inform the brain's cortex.

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> *I said to them: 'Let's work, we'll think later.' To have intentions in advance, a project, a message—no, never! You must begin by plunging in. If not, it's death. You can think—but afterwards, after it's finished. One form gives rise to another—it flows like water.*
>
> —Joan Miró*, Selected Writings and Interviews,* edited by Margit Rowell, 1998

During the 1940s, I worked at the Yerkes Laboratory of Primate Biology with its director, Karl Lashley, Harvard professor and zoologist-turned-experimental-psychologist. Those interactions with Lashley were among the most fruitful of my career. In this chapter as well as subsequent ones, I discuss the fruits of our discussions and research.

I had chosen Jacksonville, Florida, to practice neurosurgery because of its proximity to the Yerkes Laboratory. Lashley had been looking for a neurosurgeon to help operate on the brains of some of the chimpanzees housed at the laboratories. We were both delighted, therefore, when, in 1946, Lashley gave me an opportunity to inaugurate some research.

The time was propitious. Among those working at the laboratory were Roger Sperry, who later received a Nobel Prize for his experiments dividing the human brain into left and right hemispheres and was at that time transplanting the nerves of amphibians. Donald Hebb was there as a postdoctoral student, writing a book that was to become extremely influential but a bone of contention between him and Lashley. The laboratory was investigating the effect of the deprivation of vision in infancy upon later visual effectiveness, a set of studies to which I made a brief but seminal contribution. Most animals recover almost completely from temporary loss of vision in infancy, but humans develop a more permanent disability called "ambliopia ex anopsia" (weakness of vision due to failure to use the eyes). Neither Lashley nor Hebb had known this at the time, but Don Hebb immediately made this developmentally produced condition a centerpiece of his subsequent work.

Lashley was using techniques for testing primate behavior that he had refined from those already widely used in clinical neurology and those he had developed in testing rats. In Lashley's theoretical writings, based on his experience in animal research, mostly with rats, he was known for being a proponent of the view that the brain's cortex operated pretty much as an undifferentiated unit. On the basis of his research, he had formulated "the laws of mass action and equipotentiality," which referred to the findings that the change in problem-solving behavior following brain damage: a) is proportional to the amount of tissue damage and b) that the location of the damage is essentially irrelevant. Gary Boring, another Harvard professor of psychology and the historian of experimental psychology—noted that inadvertently Lashley's view of brain function made it easy for psychologists to ignore the details of brain anatomy and physiology.

Lashley's view was decidedly different from mine, which was based on my experience in brain surgery that consisted of removing tumors whose location had to be found (at a time before EEGs and brain scans) by observing the specific behavioral changes the tumors had produced.

I had read Lashley's views about the brain cortex in his 1929 book *Brain Mechanisms and Intelligence*, which I had bought second-hand for ten cents. I doubted that anyone would currently hold such views, even teasing Lashley after I got to know him by saying that his ideas seemed to be worth only the ten cents I had paid for them. But Lashley did indeed still hold these views, and he was ready to defend them. During a decades-long and rewarding friendship, we debated whether separate behavioral processes such as perception, thought, attention and volition were regulated by spatially separate brain systems, "modules" in today's terminology, or whether all such behaviors were regulated by patterns of processes distributed throughout the brain.

Two decades later, in 1960, George Miller, Eugene Galanter and I would articulate my side of the argument in our book *Plans and the Structure of Behavior* as follows:

> *There is good evidence for the age-old belief that the brain has something to do with . . . . mind. Or to use less dualistic terms, when behavioral phenomena are carved at their joints, there will be some sense in which the analysis will correspond to the way the brain is put together . . . . The procedure of looking back and forth between the two fields [psychology and neurophysiology] is not only ancient and honorable—it is always fun and occasionally useful.*

By contrast, Lashley noted that

> *Here is the dilemma. Nerve impulses are transmitted over definite, restricted paths in the sensory and motor nerves and in the central nervous system from cell to cell, through definite intercellular connections. Yet all behavior seems to be determined by masses of excitation, by the form or relations or*

*proportions of excitation within general fields of activity, without regard to particular nerve cells. It is the pattern and not the element that counts. What sort of nervous organization might be capable of responding to a pattern of excitation without limited, specialized paths of conduction? The problem is almost universal in the activities of the nervous system and some hypothesis is needed to direct further research.*

My task was set.

## Inaugural Experiments

Lashley and I decided to engage in experiments that addressed this issue. Lashley resected small strips of cortex, a cyto-architectural (cellular architectural) unit, while I chose to remove, in one session, practically all of a region that had a non-sensory input from the thalamus.

To anticipate—the results were as might be expected: Lashley was delighted to show that his resections had no effect whatsoever on the behavior of his monkeys, while my resections produced various sensory-related effects that had to be analyzed anatomically, neurophysiologically, and behaviorally by further experimentation.

I began my research by asking what might be the functions of the so-called silent areas of the brain cortex. Both in the clinic and in the experimental laboratory vast areas of cortex failed to yield their secrets. When tumors or vascular accidents damaged these regions, no consistent results were observed, and when electrical excitation was applied to the regions, no results at all were obtained.

The clinical evidence especially was puzzling. Sometimes, cognitive deficits were obtained, and these were attributed to associations that occurred between sensory inputs or between sensory inputs and higher-order brain processes. The deficits were always sensory specific: for instance, visual, tactile, or auditory (called "aphasia" when restricted to speech). As von Monikov pointed out in 1914, this raised the problem as to whether such deficits were always due to simultaneous involvement of the "silent" cortex and the sensory-specific cortex, or whether they could be produced by damage to the silent cortex alone. I set out to resolve this issue by working with selective removals of the silent cortex in monkeys without damaging the primary sensory input to the brain.

The term "association" was given to these silent cortical areas during the 1880s by Viennese neurologists because, in patients, damage, when it was extensive, resulted in cognitive disturbances that were not obtained when damage was restricted to regions that received one or another specific sensory input. The Viennese neurologists were intellectually aligned with British "associationist" philosophy. The British philosophers and, consequently, the Viennese neurologists, claimed that higher-order mental processes such as cognition are patched together in the brain by *association* from lower-order sensory processes such as vision, audition, tactile and muscle sensibilities. This view is still dominant in British and American neuroscience and philosophy.

Against the "associative" view is the fact that the cognitive disturbances are most often selectively related to one or another sensory modality. This observation led Sigmund Freud to coin the term "agnosia" (failure to know) as a modifier for such cognitive disturbances: for instance, visual agnosia, tactile agnosia. Freud did not share the associationist view. He proposed an alternative, an analysis of differential processing, in his classical book *On Aphasia*.

## The Intrinsic Cortex of the Brain

The only way to resolve whether cognitive difficul-ties could arise from damage that is restricted to the silent cortex was to work with animals, work enabling me to control the extent of removal and test the animals over a period of years. The similarity of the monkey brain to the human made the monkey an ideal choice for this research.

Monkeys have an added advantage: once a part of their brain has been removed, the rest of the brain becomes reorganized and reaches a stable condition after a few months. The monkeys can then be tested daily for years in that stable condition, allowing us to pursue a full exploration of the condition the monkey and his brain are now in. The animals are precious and we treat them as we would treat any treasured creature.

The results of my initial program were immediately successful. With my collaborators, I was able to show that parts of the silent cortex are indeed responsible for organizing sensory-specific cognitive functions, without any involvement of adjacent primary sensory systems. Monkeys have a sufficient reach of cortex that lies between the sensory receiving regions to allow careful removal without inadvertent damage to these regions or the tracts reaching them from sensory receptors. My experimental results showed that indeed sensory-specific deficiencies were produced by resections of cortex that had no direct connections with sensory receptors or motor controls. I labeled these parts of the cortex "intrinsic" (following a nomenclature introduced for the thalamus) by Jersey Rose, professor at the Johns Hopkins University and "extrinsic" (those parts of the cortex that had "direct" connections with receptors and effectors). It is now generally accepted that processing in parts of the "intrinsic" cortex is sensory specific, while in other parts a variety of inter-sensory and sensory-motor processes are organized.

> *My success was due to my bringing to bear neurosurgical techniques that I had learned to apply in humans, techniques that allowed me to gently make extensive removals of cortex without inadvertent damage to underlying and adjacent tissue. I obtained dramatic changes in behavior: the monkeys were markedly impaired when they had to make choices despite their unimpaired performances on tests of perception. I then restricted the extent of removal and demonstrated that the impairment of choices is not a "global cognitive" difficulty but is related to one or another sense modality. Today, these more restricted regions are commonly known as making up the "sensory-specific association cortex" (an oxymoron).*

A brilliantly conceived study performed on humans at the Weizmann Institute in Israel has supported the conclusions I obtained with monkeys. Subjects were shown a variety of videos and fMRIs were recorded while they were watching. No response was asked for. Rafael Malach concludes:

> *Examining fMRI activations under conditions where no report or introspective evaluation is requested— such as during an engaging movie—reveals a surprisingly limited activation . . . the very same networks which are most likely to carry high order self-related processes appear to shut off during intense sensory-motor perception.*

Local networks in the posterior visual cortex were the only ones activated by a visual percept. Simple visual stimulation engaged the extrinsic occipital region; greater involvement, as in viewing movies, engages the intrinsic visual systems of the temporal lobe. (Malach, in his presentation, used the terms "extrinsic" and "intrinsic," which I had used decades earlier.) A fronto-parietal spread of activation occurs with self-related processing such as motor planning, attentional modulation and introspection.

## Mapping the Brain

Mapping the brain's relationship to "faculties of mind" had been a favorite pastime of neurologists since the 19th century, which had spawned the heyday of phrenology.

It all began with the observations of the Viennese neuro-anatomist, Francis J. Gall (1758–1828). Gall performed autopsies on patients who had displayed ailments that could possibly be related to their brains and correlated the brain pathology he found to the disturbed behavior. He then mapped his resulting correlations and the maps became ever more intricate as his observations multiplied. This situation was complicated by decades-long popular fascination during which observations of the location of bumps on the head were substituted for dissections of the brain at autopsy.

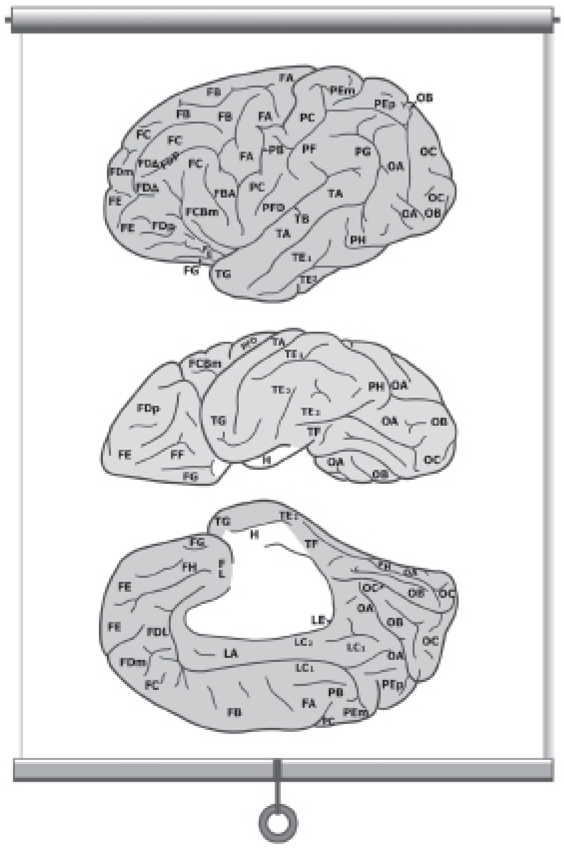
Although I had been convinced by my own neuro-surgical training and experience that useful correlations could be made relating specific behavioral disturbances to specific brain systems, these 19th- and early 20th-century maps of brain-behavioral relationships seemed ridiculous. Cognitive faculties, emotional attributes and elementary movements were assigned locations in the brain cortex in a more or less haphazard fashion.

## Reporting the Results of My Research

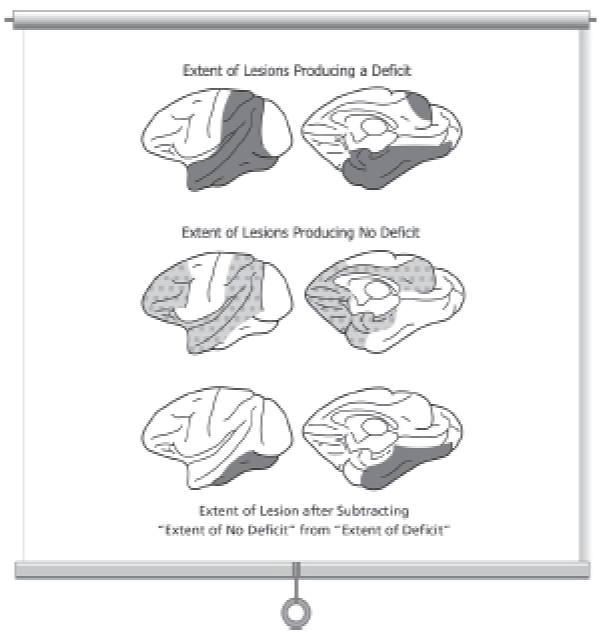
My approach to mapmaking was different. I was trying to pin down what part of the temporal lobes that Paul Bucy (with whom I took my first residency in neurosurgery) had removed was responsible for the monkeys' failure to make choices among simple visual stimuli. I realized that in order to do the temporal lobe surgery effectively, my maps must specify what it is that is being mapped—such as the connections from the thalamus, the halfway house of sensory input to our brain's cortex. Otherwise, the results of my surgery would continue to be the same hodgepodge of "localization" as that based upon brain damage in humans, which was then still in vogue.

A map of the major highways of the United States looks considerably different from one of the identical terrain that shows where mineral resources are located. Likewise, the results of damaging a part of the brain cortex would differ if one had disrupted a part of the "railroad" (the connections within the brain) versus the "mineral resources" (the sensory input to the brain).

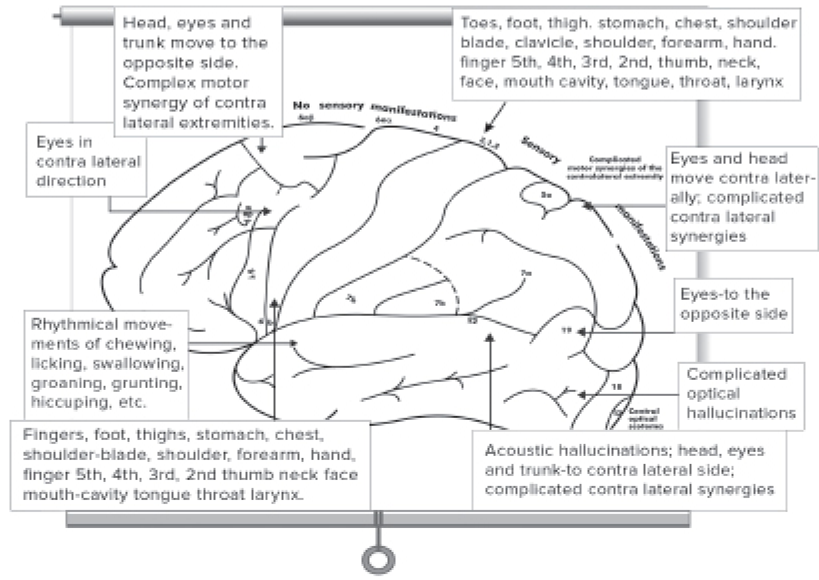
In reporting the results of my research I therefore began by presenting a series of brain maps. I did not have the resources or the money to prepare slides, so I drew the maps with colored crayons on window shades. (The maps shown here are more sophisticated than the ones I actually drew. Unfortunately, those early maps disintegrated after several decades, and I have not been able to find photographs of them.) One window shade presented what we knew of the endings in the cortex of the sensory input through the thalamus. Another window shade presented the fine architecture of the arrangement of cells in layers of the cortex. Still another noted the results of brain electrical stimulation. Finally, after the initial experiments were completed, I was able to show the effects of experimental surgical removals of cortex on specific behavioral tests.



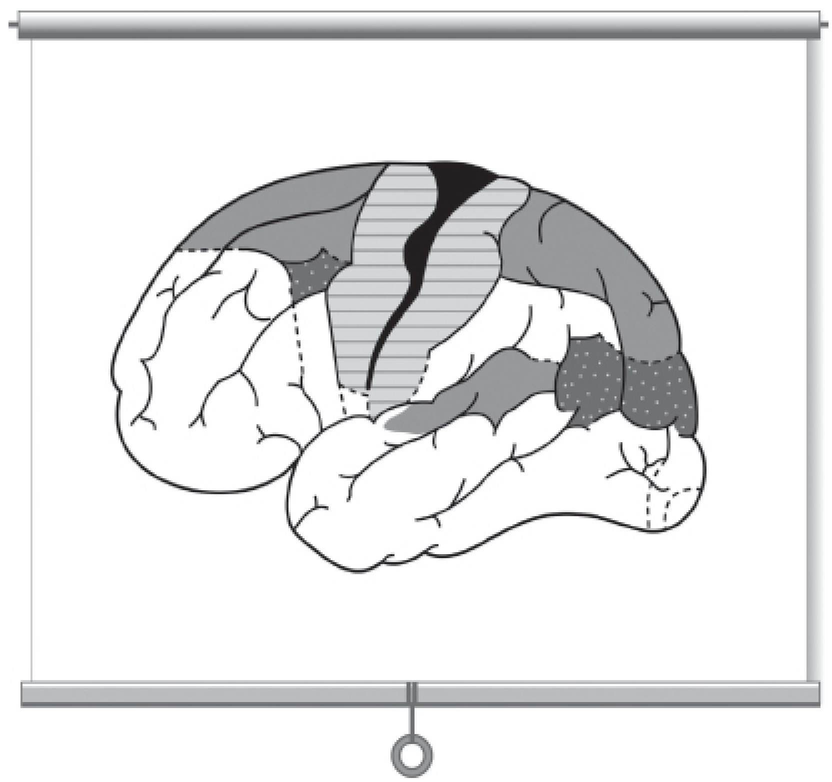

2. Cytoarchitectural map



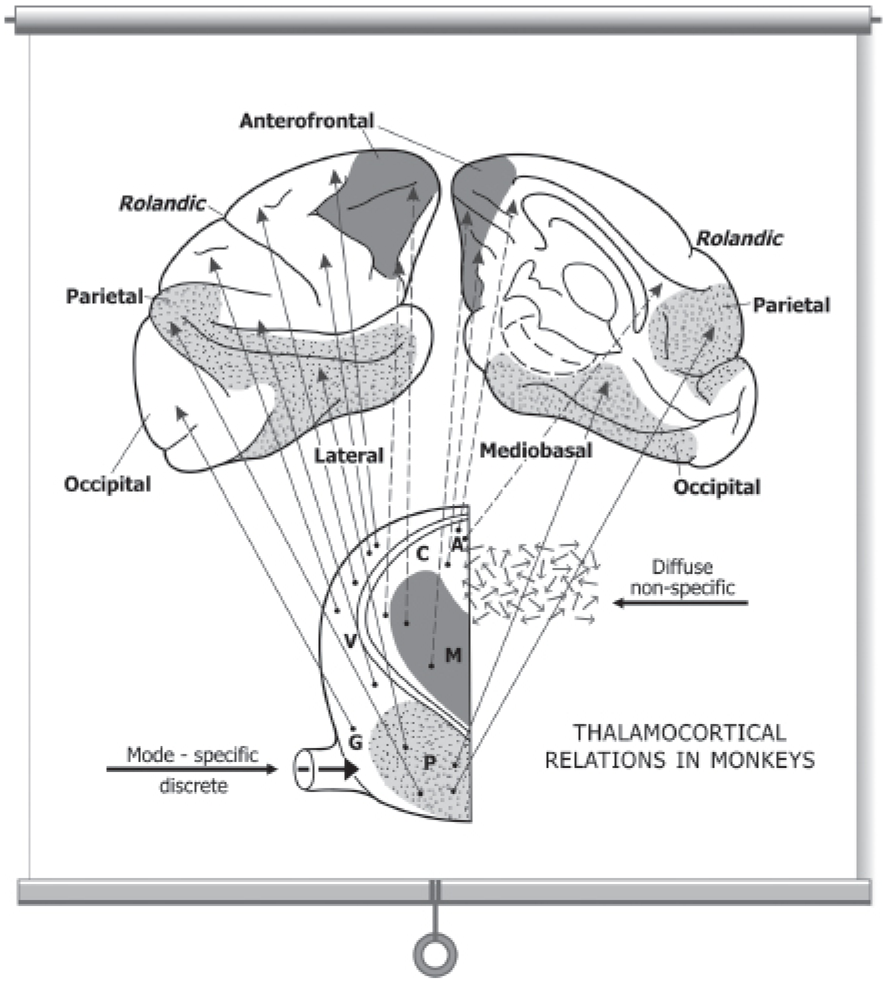

3. Mapping regions of the brain according to the effects of experimental surgical removals on visual choices




*4. Map of the functions of the cortex derived from clinical studies*



*5. Map of the anatomical output from the cortex*




*6. Map of the input to the cortex from the thalamus*

# Presenting the Results of Experiments

I arrived at each lecture site with my five window shades, found places in the lecture hall to hang them, and pulled the maps down when I needed them. The high point of this display was reached during a symposium at the 1950 meeting of the American Psychological Society at Penn State University. The symposium was chaired by Don Hebb, by now the chairman of the Department of Psychology at McGill University in Montreal. It was a time when interest among establishment experimental psychologists in brain research had reached a nadir, to the point where they had even abolished the Division of Comparative and Physiological Psychology of the American Psychological Association.

Being good friends, Hans Lukas Teuber from the Department of Neurology at New York University, Harry Harlow from the University of

Wisconsin and I as participants therefore decided to attack each other as bluntly as we could with the hope of creating some interest in the audience.

Much to our surprise, more than 800 psychologists filled the lecture hall, even sitting on the steps. The participants of the symposium each made a presentation; I started the symposium and was roundly attacked first by Harlow for “using only one or two problems to test my monkeys,” then by Teuber, who merely stated: “Just like a neurosurgeon, to hog all the space available (my window shades) only to show that we really haven’t come very far since the days of phrenology.” When it came my turn to criticize Harlow, I noted that we at Yale at least knew how to distinguish the front of the brain from the back; and after Teuber had given a most erudite and very long talk, quoting every bit of research that had been performed over the past century, I noted that he seemed not to know the literature, having missed the seminal volume on the functions of the motor cortex (edited by my neurosurgical mentor Paul Bucy, who shortly became head of the Department of Neurosurgery at Northwestern University).

The audience had quickly caught the spirit in which we were making our attacks, and the lecture hall rang with laughter. A considerable number of influential experimental psychologists have told me that their interest in brain research stemmed from that symposium.

I published my critique of 19th-century mapping procedures in a 1954 paper titled “Toward a Science of Neuro-psychology: Method and Data.” By this time, I felt that brain mapmaking, even when carefully based on sustainable correlations, was not sufficient to constitute a science. Just because we can show by electrical recording or by clinical or surgical damage that a select place in the brain is involved in color vision does not mean that it is *the* or even *a* “center” for processing color. We need to establish by behavioral techniques (for instance, tests of form vision) what else those cells in that location in the brain are doing—and then we must also show, through carefully controlled physiological experiments (for instance, by electrical stimulation or electrode recording), how these particular parts of the brain do what they do.

## Beyond Correlation

Correlating an individual's experience or his test behavior with a restricted brain location is a first step, but is not enough to provide an understanding of the brain-behavior-experience relationship. Currently, I am finding it necessary to stress this caveat once again with the advent of the new non-invasive brain-imaging techniques that are mostly being used to map correlations between a particular human experience or a particular test behavior with particular locations in the brain.

Unfortunately, many of the mistakes made during the 19th century are being made again in the 21st. On the brain side, finding "mirror neurons" matters much to materialists who feel that matter has now been shown to mirror our feelings and perceptions. But, as David Marr (now deceased) of the Massachusetts Institute of Technology pointed out, all we do with such microelectrode findings is remove the problem of understanding a process —in this case of imitation and empathy—from ourselves to the brain. We still are no further in understanding the "how" of these processes.

At the behavioral level of inquiry there is a similar lack of understanding. There is almost no effort being made to classify the behaviors that are being correlated with a particular locus in the brain. What do the behaviors have in common that are being correlated with activity in the cingulate gyrus (or in the anterior insular cortex)? And how are these behaviors grounded in what we know about the physiology of these parts of the brain?

When relations of commonalities between behavior and parts of the brain are noted, they are often mistaken. "Everyone knows the limbic systems of the brain deal with our emotions." This would be a nice generalization—except for the observation that when damage to the human limbic system occurs, a certain kind of memory, not human emotion is impaired.

And further—much has been made of the fact that the amygdala deal with "fear." Fear is based on pain. The threshold for feeling pain remains intact after the removal of the amygdala. Fear is also based on memory of pain. Is memory the contribution of the amygdala to fear? If so, what other memory processes do the amygdala serve? Chapters 13 and 14 explore these issues

Among other issues, the chapters of *The Form Within* recount the research accomplished during the early part of the second half of the 20th century that provide answers to these issues—answers that were forgotten or swept under the rug by subsequent generations of investigators.

Mapping correlations, even when done properly, is only a first step in reaching an understanding of the processes involved in relating brain to behavior and to mind— correlations do not tell us "the particular go" of a relationship.

As David Hume pointed out toward the end of the 17th century, the correlation between a cock crowing and the sun rising needs a Copernican context within which it can be understood. Here in *The Form Within,* I shall provide the context within which the correlations revealed by the technique of brain imaging need to be viewed in order to grasp the complex relationships between our experience, our behavior and our brain. To do this, I have had to provide a richer understanding of the relationship between our actions and the brain than simply making maps, which is the epitome of exploring form as shape. Sensitized by my discussions with Lashley, without overtly articulating what I was doing in my research, I thus undertook to explore form as pattern.

# Chapter 2
## Metaphors and Models

Wherein I trace my discovery of holographic-like patterns of brain processing.

> *There is still no discipline of mathematical idea analysis from a cognitive perspective, namely to apply the science of mind to mathematics—no cognitive science of mathematics.*
>
> *A discipline of this sort is needed for a simple reason: Mathematics is deep, fundamental, and essential to the human experience. As such, it is crying to be understood. It has not been.*
>
> *It is up to cognitive science and the neurosciences to do what mathematics itself cannot do—namely apply the science of mind to human mathematical ideas.*
>
> —George Lakoff and Rafael Núñez, *Where Mathematics Comes From*

## An Early Observation

In the late 1930s, the University of Chicago neurophysiologist Ralph Gerard demonstrated to those of us who were working in his lab that a cut made in the brain cortex did not prevent the transmission of an electrical current across the cut, as long as the severed parts of the brain remained in some sort of contact. I was fascinated by the observation that a crude electrical stimulus could propagate across severed nerves. Gerard suggested that perhaps his experimental observation could account for our perceptions, but I felt that our perceptual experience was more intricate, more patterned, and so needed a finer-grain description of electrical activity to account for it. I discussed this conjecture with Gerard and with my physics professor, asking them whether anyone had observed an extended fine-grain electrical micro-process. Gerard did not know of such a micro-process (nor did my physics professor), but he emphasized that something holistic—something more than simple connections between neurons—was important in understanding brain function.

Later, in the 1950s at Yale University, along with my colleagues, Walter Miles and Lloyd Beck, I was pondering the neural substrate of vision. While still at Chicago, I had written a medical school thesis on retinal processing in color sensation, under the supervision of the eminent vision scientist Stephen Polyak. In that paper I had suggested that beyond the receptors of the retina, the next stage of our visual processing is anatomically organized to differentiate the two or three colors to which our retinas are sensitive into a greater number of more restricted spectral bandwidths. Now, at Yale, Miles, Beck and I were frustrated by our inability to apply what I thought I had learned at Chicago about color to an understanding of vision of patterns, of form. I remember saying to them, “Wouldn’t it be wonderful if we had something like a spectral explanation for processing black-and-white patterns?”

## Brain Shapes: Gestalts

Not long afterward, the famous German Gestalt psychologist Wolfgang Köhler told me about his “direct current” hypothesis as the basis for cortical processing in vision. Here was the holistic “something” which I could relate to the results of Gerard’s neurophysiological experiment. Köhler and his fellow Gestalt psychologists believed that instead of working through the connections between neurons, our perceptions are reflected in electrical fields in the brain that actually have a geometrical shape resembling the shape of perceived objects. This view is called “geometric isomorphism” (*iso* = same and *morph* = shape). The Gestalt psychologists believed, for example, that if one is looking at a square—a geometrical shape—the electrical fields in one’s brain also have a square geometrical shape. Our brain representations will literally “picture” the significant environment of the organism, or at least caricature the Euclidian shape of the object while we are observing it.

In the mid-1950s, Köhler enthusiastically demonstrated his electrical fields to me and to my PhD students Mort Mishkin from McGill University in Montreal (later to become head of the Laboratory of Neuropsychology at the United States Institutes of Health) and Larry Weiskrantz from Harvard (later to become head of the Department of Experimental Psychology at Oxford University) during one of his visits to my laboratory at the Institute of Living, a mental hospital in Hartford, Connecticut. Köhler showed us just how the putative direct current (DC) electrical activity could anatomically account for visual and auditory perception.

Köhler would drive from Swarthmore College in Pennsylvania, where he was teaching, to my laboratory. We would put monkeys in a cage and take them to MIT, where we had access to the necessary auditory-stimulus control equipment to do our experiments. At MIT he and I were recording changes in direct current fields recorded from the auditory cortex of monkeys while we briefly turned on a loudspeaker emitting a tone.

On other occasions we would meet in New York City to work with patients who were being operated upon for clinical reasons and who gladly gave their consent to serve as subjects. In these experiments, Köhler and I would display a piece of reflective white cardboard in front of the subjects’ eyes while we made DC electrical recordings from the back of their brains, where the cortex is located that receives the nerve tracts from the eye. Indeed, as Köhler had predicted, we found that both monkey brains and human brains responded with a DC shift when we turned on a tone or displayed a white cardboard.

## More Experiments

Somewhat later (1960), another of the students in my laboratory (Robert Gumnit, an undergraduate at Harvard) performed a similar experiment to the one that Köhler and I had done on monkeys. In this new experiment, we used a series of clicking sounds and again demonstrated a DC shift, recording directly from the surface of the auditory cortex of cats as shown in the accompanying figure. Thus we successfully verified that there is a DC shift in the primary receiving areas of the brain when sensory receptors are stimulated. Furthermore, we demonstrated that the DC shift is accompanied by a shift from a slow to a fast rhythm of the EEG, the recording of the oscillatory electrical brain activity. Previously, human EEG recordings had shown that such a shift in the frequency of the EEG occurs when a person becomes attentive (for instance, by opening the eyes to view a scene, after having been in a relaxed state with eyes closed).

# A Neurophysiological Test

In order to explore directly Köhler's hypothesis that DC brain activity is involved in perception, I created electrical disturbances by implanting an irritant in the visual cortex of monkeys. To create the irritation, I filled small silver discs with "amphogel," aluminum hydroxide cream, a popular medication used for peptic ulcers at the time. I then placed a dozen of the discs onto the visual cortex of each of the monkeys' two hemispheres. Amphogel (or alternatively, penicillin), when applied to the brain cortex, produces electrical disturbances similar to those that initiate epileptic seizures—large slow waves and "spikes"—a total disruption of the normal EEG patterns. I tested the monkeys' ability to distinguish very fine horizontal lines from fine vertical lines. I expected that, once the electrical recordings from the monkeys' visual cortex indicated that electrical "seizures" had commenced, the monkeys' ability to distinguish the lines would be impaired or even totally lost.

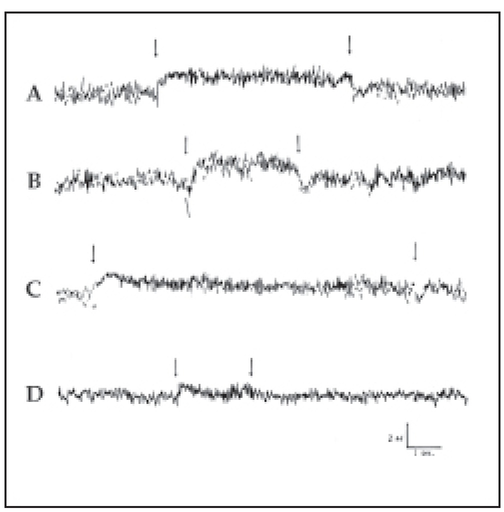
Contrary to my expectation, the monkeys were able to distinguish the lines and performed the task without any deficiency. They were able to "perceive"—that is, to distinguish whether the lines were vertical or horizontal"—even though the normal pattern of electrical waves recorded from their brains had been disrupted. Therefore, "geometric isomorphism"—the matching of the internal shape of electrical brain activity to an external form"—did not explain what was happening in the brain, at least with respect to visual perception.

I told Köhler of my results. "Now that you have disproved not only my theory of cortical function in perception, but everyone else's as well, what are you going to do?" he asked. I answered, "I'll keep my mouth shut."

And indeed, since I had no answer to explain my results, when, two years later, I transferred from Yale to Stanford University, I declined to teach a course on brain mechanisms in sensation and perception. I had to wait a few years for a more constructive answer to the problem.

## What the Experiments Did Show

Although the experiments I had conducted had effectively demonstrated that the shape of what we see is not "mirrored" by the shape of electrical activity in the brain, as Köhler had believed, my research did show something very surprising and intriguing: When the brain electrical activity was disrupted by epileptic seizures, it took the monkeys seven times longer than usual to learn the same tasks. However, once the animals started to learn, the slope of the learning curve was identical to the rapidity of learning by normal monkeys. Only the commencement of learning had been delayed. The abnormally long delay, which also occurs in mentally retarded children, may be due to an unusually long time taken to create the proper background brain activity necessary for learning to start. (More on this shortly.)



*6. Direct Current Field responses from auditory area in response to auditory stimulation. (A) Shift in response to white noise. (B) Shift in response to tone of 4000 Hertz. (C) Shift in response to white noise returning to baseline before end of auditory stimulation. (D) Response to 50 clicks/sec. returning to baseline before end of stimulation. (From Gumnit, 1960.)*

My finding came about as a consequence of the fact that all of the implantations of aluminum hydroxide cream had not produced an epileptic focus. My testing, prior to implantation, of the animals that did not show a seizure pattern was therefore wasted. So, I began to implant the epileptogenic cream before commencing testing, and to limit the testing to those monkeys who had already developed the electrical seizure pattern. Thus I was inadvertently testing the monkeys who had developed seizure patterns for their ability to learn as well as their ability to perceive.

The delay in learning had to be examined further. So, in the late 1950s, I devised, along with John Stamm, a postdoctoral fellow in my Hartford lab, another series of experiments in which we imposed a DC current across the cortex from surface to depth. We found that a cathodal (negative-going) current delayed learning while an anodal (positive-going) current enhanced it.

What we had demonstrated in these experiments was that direct currents in the brain cortex *influence attention and learning, but not perception.*

## DC Currents and States of Awareness

More recently, during the 1980s, one of the postdoctoral fellows in my laboratory at Stanford, when he returned to his laboratory in Vienna, Austria, demonstrated a large *downward* shift in the DC current recorded from the scalp during sleep. This was of great interest to me because Sigmund Freud had described such a shift in his 1895 paper “A Project for a Scientific Psychology.” I assume that one or more of his colleagues, using galvanometers, had made such a demonstration, but there is no actual record that such experiments had been done.

Even more recently, a large *upward* shift in the DC current was recorded from Sufi and other Islamic subjects while they were in a trance that made it possible for them to painlessly put ice picks through their cheeks and to perform other such ordinarily injurious feats, not only without pain but also without bleeding or tissue damage. These same individuals when not in a trance respond with pain, bleeding and tissue damage as we all do when injured.

Scientific exploration had come up with some most unexpected rewards: Looking for brain correlates of perception proved to be a dead end but revealed surprising results that challenge us to understand the brain processes operating during attention, learning and states of awareness.

As Gerard had argued during my Chicago days, direct (DC) currents must be important for something, but as I had surmised, they are too global to account for the fine structure of the patterns we experience and remember. What we needed for perception and memory was something more like micro-currents. Fortunately, those micro-currents were to appear in a fascinating context during the next decade.

## Perception Revisited

It was not until the early 1960s, a few years into my tenure at Stanford, that the issue of brain processes in perception would confront me once again. Ernest (Jack) Hilgard, my colleague in psychology at Stanford, was preparing an update of his introductory psychology text and asked me to contribute something about the status of our current knowledge regarding the role that brain physiology played in perception. I answered that I was very dissatisfied with what we knew. I described the experiments, conducted both by myself and others, that had disproved Köhler's belief that perception could be ascribed to direct current brain electrical fields shaped like (isomorphic with) envisioned patterns.

Further, I noted that David Hubel and Thorsten Wiesel had recently shown that elongated stimuli, such as lines and edges, were the most successful shapes to stimulate neurons in the primary visual receiving cortex. They had suggested that perception might result from something like the construction of stick figures from these elementary sensitivities. However, I pointed out, this proposal wouldn't explain the fact that much of our perception involves patterns produced by shadings and textures—not just lines or edges. For me, the stick-figure concept failed to provide a satisfactory explanation of how our brain organizes our perceptual process. Hilgard asked me to give this important issue some further thought. We met again about a week later, but I still had nothing to offer.

Hilgard, ordinarily a very kind and patient person, seemed just a bit peeved, and declared that he did not have the luxury of procrastination. He had to have something to say in his book, which was due for publication. He asked me to come up with a viable alternative to the ones I had already disproved or so summarily dismissed.

## Engaging Lashley

I could see only one alternative, one that provided a middle way between the direct currents of Köhler and the lines and stick figures of Hubel and Wiesel. Years earlier, during the 1940s, when I had been involved in research at the Yerkes Laboratory, its director Karl Lashley had suggested that interference patterns among wave fronts in brain electrical activity could organize not only our perceptions but also our memory. Lashley, a zoologist, had taken as his model for patterning perception those developmental patterns that form a fetus from the blastula stage to the fully developed embryo. Already, at the turn of the 19th century, the American zoologist Jacques Loeb had suggested that "force lines" guide such development. At about the same period, A. Goldscheider, a German neurologist, had wondered if such force lines might also account for how the brain forms our patterns of perceptions.

Lashley's theory of interference patterns among wave fronts of electrical activity in the brain had seemed to suit my earlier intuitions regarding patterned (as opposed to DC) brain electrical activity. However, Lashley and I had discussed interference patterns repeatedly without coming up with any idea of what micro-wave fronts might look like in the brain. Nor could we figure out how, if they were there, they might account for anything at either the behavioral or the perceptual level.

Our discussions became somewhat uncomfortable with regard to a book that Lashley's postdoctoral student, Donald Hebb, was writing at the time. Lashley declined to hold a colloquium to discuss Hebb's book but told me privately that he didn't agree with Hebb's formulation. Hebb was proposing that our perception is organized by the formation of "cell assemblies" in the brain. Lashley could not articulate exactly what his objections were: "Hebb is correct in all his details, but more generally, he's just oh so wrong." Hebb was deeply hurt when Lashley refused to write a preface to his book—which nonetheless came to be a most influential contribution to the brain/behavioral sciences.

In hindsight, it is clear that Hebb was addressing brain circuitry, while Lashley, even at such an early date, was groping for an understanding of the brain's deeper connectivity and what that might mean in the larger scheme of psychological processes.

With respect to my colleague Jack Hilgard's problem of needing an answer about brain processes in perception in time for his publication date, I took his query to my lab group, outlining both my objections to Köhler's DC fields and to Hubel and Wiesel's stick figures. I suggested that since there were no other alternatives available right now, perhaps Lashley's proposal of interference patterns might be worth pursuing. Not totally tongue-in-cheek, I noted that Lashley's proposal had the advantage that we could not object to something when we had no clue of what was involved.

## Microprocessing at Last

Within a few days of my encounters with Jack Hilgard, a postdoctoral fellow in my laboratory, Nico Spinelli, brought us an article by the eminent neurophysiologist John Eccles that had appeared in 1958 in *Scientific American*. In this article, Eccles pointed out that, although we could only examine synapses—junctions between brain cells—one by one, the branching of large fiber axons into fine fibers just as they are approaching a synapse makes it necessary for us to regard the electrical activity occurring in these finefibered branches as forming a wave front. This was one of those "aha" moments scientists like me are always hoping for. I immediately recognized that such wave fronts when reaching synapses from different directions, would provide exactly those long-sought-after interference patterns Lash-ley had proposed.

Despite my excitement at this instant realization, I also felt like an utter fool. The answer to my years of discussion with Lashley about how such interference patterns among micro-waves could be generated in the brain had all the time been staring us both in the face—and neither of us had had the wit to see it.

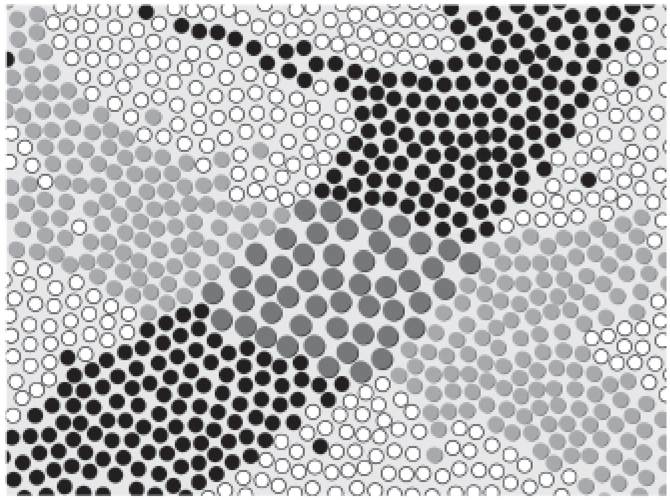
## Brain Waves, Interference Patterns and Holography

Fortunately for my self-respect, (and only because “P” comes before “S” on the mailing list) I received my next issue of *Scientific American* before Nico Spinelli received his. In that issue, two optical engineers at the University of Indiana, Emmet Leith and J. Upaticks, described how the recording of interference patterns on photographic film had tremendously enhanced the storage capacity and retrieval of images. Images could now readily be recovered from the “store” by a procedure (described below) that had actually been developed by the Hungarian mathematician Dennis Gabor almost two decades earlier. Gabor had hoped to increase the resolution of electron microscopy. He had called his procedure “holography.”

Gabor’s mathematical holographic procedure, which Leith had later used to produce a holographic process, was a miraculous answer to the very question Jack Hilgard had posed to me about perception just a few weeks earlier. Everything in a pattern that we perceive—shading, detail and texture—could be accomplished with ease through the holographic process.

Russell and Karen DeValois’s 1988 book *Spatial Vision* as well as my own 1991 book *Brain and Perception* would provide detailed accounts of each of our own experimental results and those of others who, over the intervening decades, used Gabor’s mathematics to describe the receptive fields of the visual system.

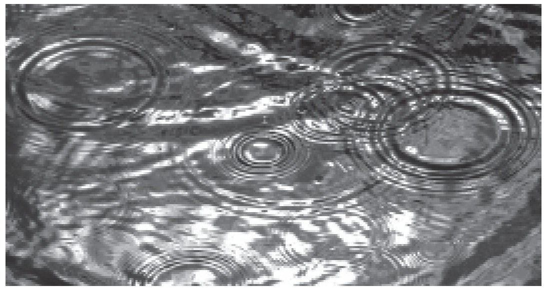
Unfortunately, at the time Hilgard’s textbook revision was due, these insights were as yet too untested to provide him with the material he needed. But making visible the processing of holographic images showed me the critical role mathematics would play in our ability to grasp and interpret the complexity of the brain/ mind relationship.



*8. Interference patterns formed by wave fronts of synapses*

# What is the Holographic Process?

Leith actualized (made visible) Gabor's mathematical holographic procedure, but other striking examples of this process are visible to us in nature every day. A holographic process is nothing more than an interference pattern created by the interaction of two or more waves. For example, if you throw a pebble into a pond, a series of concentric circles—waves—will expand outward. If you drop two pebbles side-by-side, two sets of waves will expand until they intersect. At the point where the circles of waves cross, they reinforce or diminish each other, creating what we call an interference pattern. A remarkable aspect of these interference patterns is that the information of exactly when and where the pebbles hit the pond is spread throughout the surface of the water—and that the place and moment that the pebbles had hit the pond can be reconstructed from the pattern. We accomplish this by simply reversing the process: if we filmed it, we run the film backward; or, if we used Gabor's mathematics, we simply invert the transformation. Thus, the location and time of the point of origin can always be recovered from the interference pattern.



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# Try It Yourself

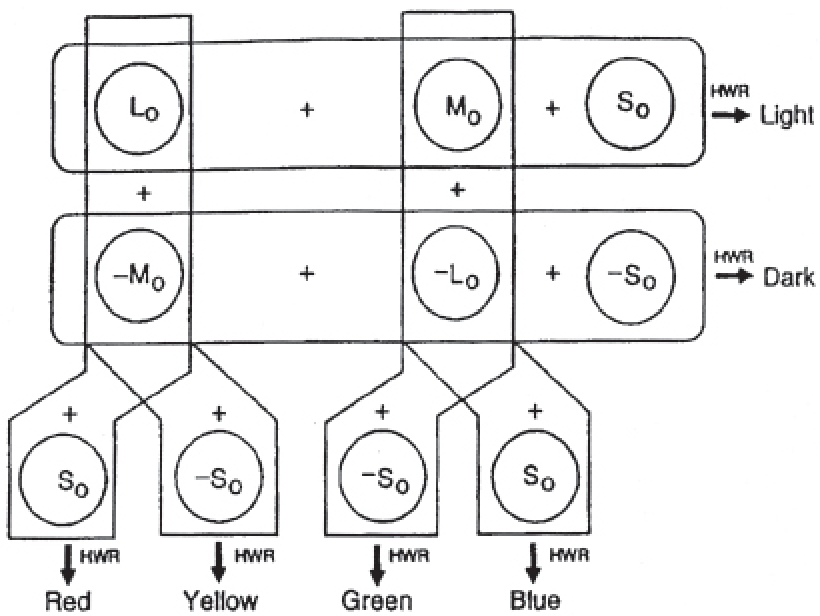
You can simply and directly demonstrate how the holographic process works by using an ordinary slide projector. Project the image of a slide on a large white screen and then remove the lens of the slide projector. Now you see nothing on the screen but a big bright white blur of scattered light. But if you take a pair of ordinary reading glasses and hold them in the array of light between the projector and the screen, you will see two images appear on the screen wherever you place the two lenses of your glasses. No matter where you hold the reading glasses in the scatter field of the projected light, the two lenses will create two distinct images of your original slide on the screen. If four lenses are used, four images will appear on the screen. A hundred lenses would produce a hundred images. The "information," the pattern contained in the original image, in the absence of the lens, becomes spread, scattered. The lens restores the image. As the demonstration using the projector indicates, lenses such as those in our eyes or in the slide projector perform a transformation on the "information" that is scattered in the light: patterns that seem to be irretrievably annihilated are in fact still present in every portion of the scattered light, as the evidence from the use of the eyeglass lenses demonstrates.

Gabor based his holographic procedure on transforming the space and time coordinates of our experience, within which we navigate every day of our lives, into a spectrum of interference patterns. My hope from the earliest days of my research had now been realized: that we might one day achieve an understanding of form in terms of spectra akin to that which we had for our perception of spectra of color.

But the form that the answer to my hopes took, and the broader implication for our understanding of how we navigate our universe (as indicated in Appendix A), was and still is to me, totally surprising.

The spectral processing of color and the spectral processing of patterns must become meshed in the brain. Russ and Karen DeValois, on the basis of their research, have been able to construct a single neurological network that can process both color and pattern, depending on how that network is addressed. The addressing can be initiated either by the visual input or from a higher-order brain process. Their network accounts for the observation that we rarely see color apart from form.

Chapters 4 to 8 tell the story of how the scientific community has dealt with the insights derived from these new ways of thinking, ways derived from the metaphors and models that have been outlined in the current chapter.




*10. A complete diagram of the proposed stage 3. Russ and Karen DeValois's Spatial Vision*

# Chapter 3
## A Biological Imperative

Wherein I describe the experimental results that provided substance to the self-organizing processes in the brain.

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*In 1957 it was possible to say . . . 'these considerations also lead us to the suggestion that much of normal nervous function occurs without impulses but is mediated by graded activity.' . . . I referred to Gerard (1941) who influenced me most in this view which remained for a long time ignored in the conventional orthodoxy. I propose that a 'circuit' in our context of nervous tissue is an oversimplified abstraction. . . . that, in fact there are many types of signals and forms of response, often skipping over neighbors—and acting upon more or less specific classes of nearby or even remote elements. Instead of the usual terms 'neural net' or 'local circuit' I would suggest we think of a neural throng, a form of densely packed social gathering with more structure and goals than a mob.*

—T. H. Bullock, 1981

## Brain Patterns

My 1971 book *Languages of the Brain* begins:

> *'I love you.' It was spring in Paris and the words held the delightful flavor of a 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 curvaceous blonde beauty, however, but generated by a small shiny metal device in the hands of a Swedish psycholinguist.*
>
> *The device impressed all of us with the simplicity of its design. The loudspeaker was controlled by only two knobs. One knob altered the state of an electronic circuit that represented the tensions of the vocal apparatus; the other regulated the pulses generated by a circuit that simulated the plosions of air puffs striking the pharynx.*
>
> *Could this simple device be relevant to man's study of himself? Might not all behavior be generated and controlled by a neural mechanism equally simple? Is the nervous system a "two knob" dual process mechanism in which one process is expressed in terms of neuroelectric states and the other in terms of distinct pulsatile operators on those states? That the nervous system does, in fact, operate by impulses has been well documented. The existence of neuroelectric states in the brain has also been established, but this evidence and its significance to the study of psychology has been slow to gain acceptance even in neuro-physiology. We therefore need to examine the evidence that makes a two-process model of brain function possible.*

What needed to be established is that brain patterns are formed by interactions between: 1) a formative "web" of dynamic states that involves the fine branches of brain cells (called "dendrites," Latin for "small branches") and their connections (membranes, glial cells, chemical synapses and electrical junctions) and 2) "circuits" composed of large fibers (axons) that operate in such a way as a) to sample the web, and b) to convey the resulting samples from one brain region to another and also convey samples from sensory receptors to the brain and from the brain to glands and muscles.

*In a sense, the web composes the form of a process, while the circuits address that form, enabling contemplation or action.*

## The Retina: Key to Formative Brain Processing

In contrast to the rather straightforward use of the experimental technique of microelectrode recording to understand the form of processing in the circuits of the brain, the small diameter of the dendritic branches makes the electrical recordings of the web a real challenge. Nonetheless, techniques were developed early on, in the 1950s, that allowed us to map the receptive fields that are formed in the dendritic web. How these mappings are made is described in the following sections.

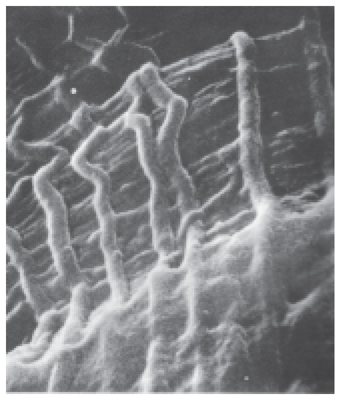
An anecdote highlights the issue: In the early 1970s, I attended an International Physiological Congress where the keynote speaker was the noted British scientist A. L. Hodgkin. Two decades earlier, he had received the Nobel Prize, with A. F. Huxley, for the elegant mathematical description of the results of their experiments on the generation of nerve impulses.

Hodgkin began his address with the question: “What does one do after winning the Nobel Prize?”

He had thought a while about this, he said, and realized that he had not become a neurophysiologist merely to describe how a membrane generates a nerve impulse. No, he was interested in how the brain works—how it regulates the way the body operates, and how it makes our conscious experience possible. What followed his realization, he told us, was a brief period of depression: alas, he was not a brain surgeon and didn’t have the tools to address the problems that initially had challenged him. (His prize-winning experiments were actually done on the very large nerve fibers of crayfish.) One morning, however, Hodgkin had awakened with a promising insight: God, he realized, had put a piece of brain outside the skull, just so that physiologists such as himself could study it without having to drill holes to get at it!

That piece of “brain” is the retina of the eye. The retina, like the brain cortex, is made up of layers of nerve cells with the same fine-fibered profusion of branches. These fine fibers are present between the layers that reach from the receptors inward, and they also make up a feltwork, a web, within each of these layers. Hodgkin went to work on the retina at once.

He told us that he was surprised and amazed by what he found—or rather by what he didn't find: Over the next decade, in his many studies, he hardly ever encountered a nerve impulse, except at the very final stage of processing—the stage where those nerves with large diameters, large axons, generate signals that are transmitted to the brain. Therefore, everything we "see" is first processed by the fine fibers of the retina before any nerve impulses are actually generated.



*11. The Fine-Fibered Neuro-Nodal Web in the Retina*

*Scanning electron micrograph showing the arrangement of nerve fibers in the retina of* Necturus. *Fibers (dendrites) arise in the inner segment and course over the outer segment of a cone. Note that points of contact do not necessarily take place at nerve endings. (From Lewis, 1970.)*

The situation that Hodgkin found in the retina is identical to what occurs in the web of dendrites in the brain cortex: processing occurs in the fine fibers, and these processes compose and form the patterns of signals relayed by axons, the large nerve trunks.

## Mapping the Neuro-Nodal Web

At about the same time, in the 1950s, that Hodgkin had begun his work on the retina, I shared a panel at a conference held in 1954 at MIT with Stephen Kuffler of the Johns Hopkins University. In his presentation, Kuffler declared that the "All or None Law" of the conduction of nerve impulses had to be modified into an "All or Something Law": That the amplitude and speed of conduction of a nerve impulse is proportional to the diameter of the nerve fiber. Thus the speed of conduction and size of a nerve impulse at the fine-fibered presynaptic termination of axon branches (as well as in the fine-fibered postsynaptic dendrites) is markedly reduced, necessitating chemical boosters to make connections (or a specialized tight junction to make an ephaptic electrical connection).

Kuffler focused my thinking on the type of processing going on in the fine-fibered webs of the nervous system, a type of processing that has been largely ignored by neuro-scientists, psychologists and philosophers.

Kuffler went further: he devised a technique that allowed us, for the first time, to map what is going on in these fine-fibered webs of dendrites in the retina and the brain. Kuffler noted that in the clinic, when we test a person's vision, one of our procedures is to map his visual field by having him tell us where a spot of light is located. The visual field is defined as that part of the environment that we can see with a single eye without moving that eye. When we map the shape of the field for each eye, we can detect changes due to such things as retinal pathology, pituitary tumors impinging on the place where the optic nerves cross, strokes, or other disturbances of the brain's visual pathways.

Kuffler realized that, instead of having patients tell us when and where they see a spot, we could—even in an anesthetized animal—let their neurons tell us. The signal we use to identify whether a neuron recognizes the spot is the change in pattern of nerve impulses generated in an axon. The "receptive field" of this axon is formed by its finefibered branches and corresponds precisely, for the axon, to what the "visual field" is for a person. By this procedure, the maps we obtain of the axon's dendritic receptive field vary from brain cell to brain cell, depending upon what kind of stimulus (e.g., a spot, a line, a grating) we use in order to elicit the response: as in the case of whole brain maps, the patterns revealed by mapping depend on the procedure we use to display the micro-maps.

Kuffler's initial work with receptive fields, followed by that of others in laboratories in Sweden and then all over the world, established that the receptive fields of those axons originating in the retina appear like a bull's-eye: some of the retina's receptive fields had an *excitatory* ("on") center, while others had an *inhibitory* ("off") center, each producing a "complementary" surrounding circular band.

When he used color stimuli, the centers of those receptive fields which were formed by a response to one specific color—for instance, red —were surrounded by a ring that was sensitive to its complementary (also called its opponent) color—in the case of red: green; centers responding to yellow were surrounded by rings sensitive to blue, and so forth. Having written my medical student's thesis on the topic of retinal processing of color stimuli, I remember my excitement in hearing of Kuffler's experimental results. For the first time this made it possible for us to establish a simple classification of retinal processing of color and to begin to construct a model of the brain's role in organizing color perception.

In addition, we learned that in more central parts of the brain's visual system, in the halfway house of the paths from the retina to the cortex—the thalamus ("chamber," in Latin)—the receptive field maps have more rings, each ring alternating, as before, between excitation and inhibition—or between complementary colors.

However, in initial trials at the brain's cortex, the technique of moving a spot in front of an eye at first failed to produce any consistent response. It took an accident, a light somewhat out of focus, to produce an *elongated* stimulus, to provide excellent and interesting responses: neurons were selective of the orientation of the stimulus; that is, different orientations of the elongated "line" stimulus activated different neurons.

Furthermore, for those neurons that responded, the map of the receptive field became elongated, with some fields having inhibitory "flanks," like elongated rings of the bulls-eye, while others without such flanks looked more like flat planes. We've all learned in high school geometry that by putting together points we can make lines and putting together lines at various orientations we can compose stick figures and planes. Perhaps, thought the scientists, those brain processes that involve our perceptions also operate according to the rules of geometry that we all had learned in school.

The scientific community became very excited by this prospect, *but this interpretation of our visual process in terms of shape, as is the case with regard to brain maps, though easy to understand, fails to explain many aspects of the relationship of our brain to our experience.*

In time, another interpretation, which I shall explore in the next chapters of *The Form Within,* would uncover the patterns underlying these shapes. A group of laboratories, including mine, would provide us a more encompassing view of processing percepts and acts by the brain.

## The Two Processes That Form Patterns in Our Brains

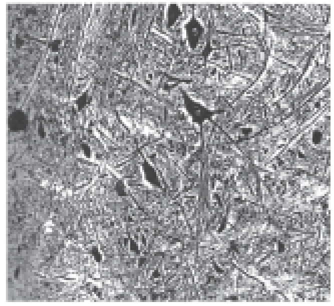
To review briefly: The circuits of our brain consisting of large nerve fibers, axons, have sufficient girth to sustain the transmission of nerve impulses produced by complete depolarization—the discharge of the electrical polarization—of their membranes. The nerve impulses, acting like sparks, can travel along the nerve over long distances.

The nature of processing in circuits of the brain has been well documented and is therefore well established within the neuroscience community. Neuroscientists have focused on nerve impulse transmission in large nerve fibers because, due to the available experimental tools over the past century, this aspect of brain function has been more accessible to us and has yielded results that are easy to interpret and to understand. (To anticipate a discussion later in this chapter: circuits are of two sorts, flexible short-range assemblies and fixed long-range connections.)

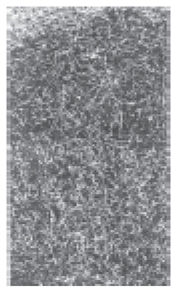
By contrast, the fine fibers composing the web—the branches or dendrites of nerve cells—cannot sustain nerve impulse conduction the way axons can. The electrical activity of dendrites rarely "sparks" but oscillates between excitation and inhibition; thus, dendritic activity occurs locally, forming patches or nodes of synchronized oscillating activity.

The dendritic patches, the nodes, are not only produced by electrical and chemical activity at the junctions (synapses and ephapses) that connect the fine fibers, but also independently of what is going on at these junctions: Dendrites have been found to secrete chemical modulators in conjunction with the glia or "glue" cells that surround them. The patches of activity that are carried on within the fine fibers in our brain thus form a neuro-nodal web.

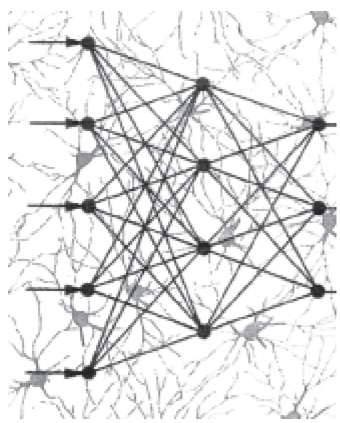
Unlike the longer-range activity of large nerve fibers, the coordinating influence of dendrites on neighboring regions of the brain results only from a local spread of excitation. The fact that dendritic processing is restricted to such a local patch posed a serious problem for me back in the mid-1960s when I first suggested its importance. How could the sort of global brain activity that is necessary to our thought, perception and memory be achieved from such isolated activities in small patches? Surprisingly, I found the resolution to my quandary in astrophysics.



*12. The Dendritic Web*



*13. The Cortical Chem-Web Demonstrated by Staining Acetyl Choline Esterase Receptors*



*14. The Neuro-Nodal Web*

Astrophysicists need to be able to explore large reaches of sky, but telescopes could capture only a small portion at any one viewing. They finally solved this problem by converting the images obtained through the telescope using a mathematical equation, the Fourier transformation— the procedure that Gabor used to invent holography—that will be referred to again and again in much of the rest of this book. The procedure works by Fourier-transforming adjacent images obtained by the telescope; patching them together and performing another transformation, the reverse of the initial transformation, on the patched whole, to give a usable image of large expanses of sky. This same procedure is now used routinely in current image processing in hospitals such as PET scans and fMRI.

When the formative processing web provided by the dendrites has to be accessed by the rest of the brain, axons relay the results of these interactions to other parts of the brain or to receptors and effectors in the body.

The neuroscience community as a whole has until recently tended to disregard completely what is going on in the fine-fibered branches, the dendrites, as well as ignoring the *importance* of what goes on within these webs, as illustrated above in the neuro-nodal and chem-webs. This despite the statements such as those by George Bishop, professor at Washington University in St. Louis, considered at the time to be the dean of neurophysiologists (during the 1950s), who repeatedly stated that processing in the nervous system is a function of its fine fibers; the results of processing are conveyed to other parts of the nervous system and to sensory and motor systems by circuits of axons. Another influential neuroscientist, Ted Bullock, professor at the University of California at San Diego, on the basis of his research experience, put it even more bluntly and detailed what is actually occurring in the fine-fibered processes, as described in the quotation that inaugurated this chapter.

His description of neural transactions as “a densely packed social gathering in which connections often skip neighbors and act upon more or less specific classes of nearby or even remote elements” fits what computer scientists describe as the makings of self-organizing systems.

Hopefully, in the past few years the scene has at last begun to change as heralded, for example, by an excellent review by R. Douglas Fields in the June/July 2006 issue of *Scientific American MIND* of the circuit vs. the web-like processing in the brain cortex.

## Flexible Assemblies and Executive Circuits

The dendritic *formative* process is directly addressed by the circuitry of the brain, organized along two very different principles: 1) by local circuits to form flexible cell assemblies that, in turn, are addressed 2) by long-range “*executive*” circuits of larger axons.

The short-range flexible assemblies directly sample the neuro-nodal web in an organization called “heterarchical” by which the members connected interact on an equal level. These heterarchical organizations are the basis of self-organizing procedures in the formation of complex systems.

The long-range, more or less fixed connections form a “hierarchy;” that is, each level of organization controls a lower level.

In practice, the distinction between flexible assemblies and long-range circuits is the distinction between gray and white matter in the cortex. I have made fairly extensive removals limited to gray matter (performed with a specially designed suction apparatus that would not sever the white fibers) with only minor effects on behavior. When, however, the removals invade the white matter underlying the cells and their short-range connections that compose the gray matter, extensive deficits in behavior result. (The distinction between resections of gray and white matter came to my attention when evaluating the effects of lesions of parts of the prefrontal cortex. My resections were carefully limited to gray matter; others were not so careful, so their resections invaded the white matter connecting other parts of the prefrontal cortex, making their results uninterpretable.)

Once again, the long-range, more or less fixed connections form a “hierarchy,” that is, each level of organization controls a lower level.

The two principles, heterarchy and hierarchy appear to be ubiquitous wherever the members of an organization with equal potential for interaction become organized.

Warren McCulloch, a lifelong friend and one of the founders of cybernetics, the study of control systems, used to enjoy telling the following story regarding the risk of making decisions that are dependent on heterarchical controls:

After the World War I battle of Jutland, in which many British ships were disastrously sunk, the British and American navies changed from a hierarchical control organization, in which every decision had to be referred to the admiralty, to a heterarchical organization in which control and the formation of a relevant organization was vested in whomever had information relevant to the context of the situation. During World War II, two Japanese air squadrons simultaneously attacked an American fleet in the South Pacific from different directions. These attacks were spotted by different sections of our fleet, the information was relayed to the relevant sections of our fleet and, as was the practice, they were taken as commands. As a result, the two sections of our fleet steamed off in separate directions to deal with the separate oncoming attacks, leaving the admiral on his centrally located ship completely unprotected. Fortunately, both Japanese attacking forces were routed, leaving the fleet intact. McCulloch liked to suggest that this story might serve as a parable for when we are of two minds in a situation in which we are facing an important decision.

I have learned even more about the nature of human heterarchical and hierarchical self-organizing systems from Raymond Trevor Bradley. Bradley did his doctoral dissertation at Columbia University in the 1970s, observing several communes and meticulously documenting the way each member of such a closely articulated community engaged each of the other members. Bradley (*Charisma and Social Structure: A Study of Love and Power, Wholeness and Transformation*, 1987) found that each commune was self-organized by a heterarchical structure made up of personal emotional transactions as well as a hierarchical structure that guided the motivations of the overall commune as a whole. Further, the hierarchy was composed of heterarchical cliques that were often connected by a single bond between a member of one clique and a member of another.

Those communes that remained stable over a number of years were characterized by a balanced expression between heterarchical and hierarchical processing. Bradley's results held for all communes whether they had strong leadership, temporary leadership, or no consistent leadership. If the motivational hierarchy overwhelmed the emotional heterarchy, the communes tended to be short-lived. Likewise, if the emotional structure overwhelmed the motivational structure, the commune also failed to survive.

The striking parallels between social and brain processing brought Bradley and me together, and we have collaborated (e.g., Pribram, K. H. and R. T. Bradley, *The Brain, the Me and the I*; in M. Ferrari and R. Sternberg, eds., *Self awareness: Its Nature and Development*, 1998), in several brain/ behavior/ mind studies over the years.

These parallels—parallels that compose General Systems Theory—make a good starting point for inquiry. They form the foundation of our understanding of the relationship between our world within and the world we navigate—the contents of Chapters 9 to 17.

At the same time, the parallels tell us too little. Just because a brain system and a social system have similar organizations does not tell us "the particular go," the "how" of the relation between brains and societies. For understanding the "how" we must know the specific trans-formations (changes in form) that relate the various levels of inquiry to each other—brain to body and bodies to various forms of society. I take up the nature of transformations, what it takes to transform one pattern into another, in Chapters 18 and 19.

# Chapter 4

## Features and Frequencies

Wherein I juxtapose form as shape and form as pattern as they are recorded from the brain cortex and describe the usefulness and drawbacks of each.

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> *We live in a sea of vibrations, detecting them through our senses and forming impressions of our surroundings by decoding information encrypted in these fluctuations.*
>
> —Ovidiu Lipan, "Enlightening Rhythms," *Science, 2008*

> *It sometimes appears that the resistance to accepting the evidence that cortical cells are responding to the two-dimensional Fourier components of stimuli {is due} to a general unease about positing that a complex mathematical operation similar to Fourier analysis might take place in a biological structure like cortical cells. It is almost as if this evoked, for some, a specter of a little man sitting in a corner of the cell huddled over a calculator. Nothing of the sort is of course implied: the cells carry out their processing by summation and inhibition and other physiological interactions with their receptive fields. There is no more contradiction between a functional description of some electronic component being a multiplier and its being made up of transistors and wired in a certain fashion. The one level describes the process, the other states the mechanism.*
>
> —Russell DeValois and Karen DeValois, *Spatial Vision,* 1988

In this chapter I detail for the visual system the difference between the two modes of scientific exploration discussed in earlier chapters. One of these modes explores form as shape, while the other explores form as pattern. Features can be thought of either as building blocks that determine the shape of our environment or as components of perceived patterns that we as, sentient, conscious, beings choose to focus on.

Within the research community the contrast between these two views of perception was wittily joked about as pitting "feature creatures" against "frequency freaks." Feature creatures were those who focused on "detectors" within our sensory systems, of features in our external environment —a purely "bottom-up" procedure that processes particulars into wholes. Frequency freaks, by contrast, focused on similarities between processes in the visual mode and those in the auditory (and incidentally the somatosensory) mode. For the frequency freaks, the central idea was that our visual system responds to the spectral, frequency dimension of stimulation very much as the auditory system responds to the oscillations that determine the pitch and duration of sound. The approach of the frequency freaks, therefore, is "top-down"—wholes to particulars. Within the neuroscience community, the feature creatures still hold the fortress of established opinion, but frequency freaks are gaining ascendance with every passing year.

## An Early Intuition

My initial thought processes and the research that germinated into this section of *The Form Within* reinforced my deeply felt intuition that the "feature detection" approach to understanding the role of brain processes in organizing our perceptions was of limited explanatory value.

Michael Polanyi, the Oxford physicist and philosopher of science, defined an intuition as a hunch one is willing to explore and test. (If this is not done, it's just a guess.) Polanyi also noted that an intuition is based on tacit knowledge; that is, something one knows but cannot consciously articulate. Matte Blanco, an Argentine psychoanalyst, enhanced this definition by claiming that "the unconscious" is defined by infinite sets: consciousness consists of being able to distinguish one set of experiences from another.

The "feature detection" story begins during the early 1960s, when David Hubel and Torsten Wiesel were working in Stephen Kuffler's laboratory at the Johns Hopkins University. Hubel and Wiesel had difficulty in obtaining responses from the cortical cells of cats when they used the spots of light that Kuffler had found so effective in mapping the responses in the optic nerve. As so often happens in science, their frustration was resolved accidentally, when the lens of their stimulating light source went out of focus to produce an elongation of the spot of light. The elongated "line" stimulus brought immediate results: the electrical activity of the cat's brain cells increased dramatically in response to the stimulus and, importantly, different cells responded selectively to different orientations of the elon-gated stimulus.

During the late 1960s and early 1970s, excitement was in the air: like Hubel and Wiesel, many laboratories, including mine, had been using microelectrodes to record from single nerve cells in the brain. Visual scientists were able to map the brain's responses to the stimuli they presented to the experimental subject. Choosing the stimulus most often determined what would be the response they would obtain.

Hubel and Wiesel settled on a Euclidian geometry format for choosing their visual stimulus: the bull's eye "point" receptive fields that characterized the retina and geniculate (thalamic) receptive fields could be shown to *form* lines and planes when cortical maps were made. I referred to these results in Chapter 3 as making up "stick figures" and that more sophisticated attempts at giving them three dimensions had essentially failed.

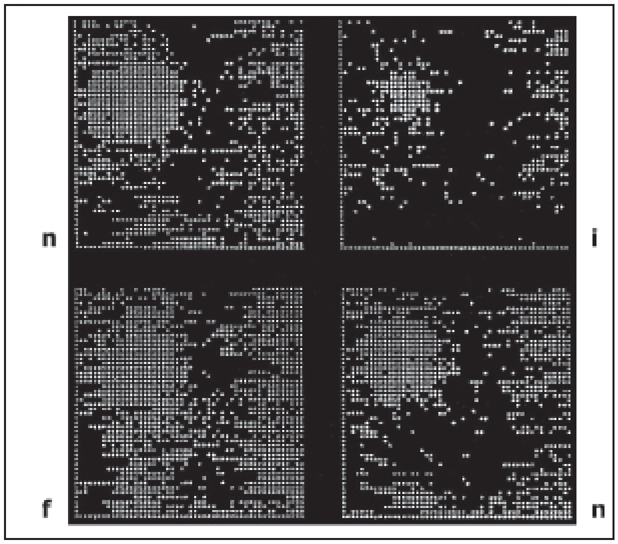
Another story, more in the Pythagorean format, and more compatible with my intuitions, surfaced about a decade later. In 1970, just as my book *Languages of the Brain* was going to press, I received a short reprint from Cambridge University visual science professor Fergus Campbell. In it he described his pioneering experiments that demonstrated that the form of visual space could profitably be described not in terms of shape, but in terms of patterns of their spatial frequency. The frequency was that of patterns of alternating dark and white stripes whose fineness could be varied. This mode of description was critical in helping to explain how the extremely fine resolution of a scene is possible in our visual perception. Attached to this reprint was a note from Fergus: "Karl—is this what you mean?" It certainly was!!

After this exciting breakthrough, I went to Cambridge several times to present my most recent findings and to get caught up with those of Campbell and of visual scientist Horace Barlow, who had recently moved back to Cambridge from the University of California at Berkeley, where we had previously interacted: he presenting his data on Cardinal cells (multiple detectors of lines) and I presenting mine on the processing of multiple lines, to each other's lab groups.

Campbell was showing that not only human subjects, but brain cells respond to specific frequencies of alternating stripes and spaces. These experiments demonstrated that the process that accounts for the extremely fine resolution of human vision is dependent on the function of the brain cortex. When the Cambridge group was given its own sub-department, I sent them a large "cookie-monster" with bulging eyes, to serve as a mascot.

Once, while visiting Fergus's laboratory, Horace Barlow came running down the hall exclaiming, "Karl, you must see this, it's right up your alley." Horace showed me changes produced on a cortical cell's receptive field map by a stimulus outside of that brain cell's receptive field. I immediately exclaimed, "A cortical MacIlvain effect!" I had remembered (not a bad feat for someone who has difficulty remembering names) that an effect called by this name had previously been shown to occur at the retina. Demonstrating such global influences on receptive fields indicated that the fields were part of a larger brain network or web. It took another three decades for this finding to be repeatedly confirmed and its importance more generally appreciated by the neuroscience community.

*These changes in the receptive fields are brought about by top-down influences from higher-order (cognitive) systems. The changes determine whether information or image processing is sought. Electrical stimulation of the inferior temporal cortex changes the form of the receptive fields to enhance information processing— as it occurs in communication processing systems. By contrast, electrical stimulation of the prefrontal cortex changes the form of the receptive fields to enhance image processing—as it is used in image processing such as PET scans, fMRI and in making correlations such as in using FFT. The changes are brought about by altering the width of the inhibitory surround of the receptive fields. Thus both information and image processes are achieved,* *depending on whether communication and computation or imaging and correlations are being addressed.*




*15. Cross sections of thalamic visual receptive fields (n) showing the influence of electrical stimulation of the inferior temporal cortex (i) and the frontal cortex (f)*

## Encounter at MIT

In the early 1970s, I was invited to present the results of these experiments at the Massachusetts Institute of Technology. The ensuing discussion centered not on the results of my experiments but—ironically, it being MIT— on my use of computers. David Hubel stated that the use of computers would ruin visual science by taking the research too far from a hands-on, direct experience necessary to understanding the results of observation. I retorted that in every experiment, in the mapping of every cell, I had to use the direct hands-on mapping before I could engage the computer to quantify my observations. I stated that in order to obtain the results that I had shown, I needed stable baselines—baselines that could only be statistically verified by the use of a computer. Only by using these baselines, could I show that the changes produced by the electrical stimulation were reliable.

Then my host, Hans-Lukas Teuber, professor and chair of the Department of Psychology at MIT, rose to support Hubel by saying that the use of computers would also ruin behavioral psychology. He was an old friend of mine (our families celebrated each Thanksgiving together), so I reminded him that my laboratory had been completely computerized since 1959, when I'd first moved to Stanford. That alone had made it possible to test 100 monkeys a day on a variety of cognitive (rather than conditioning) tasks. I pointed out that he should be pleased, since he was a severe critic of operant conditioning as a model for understanding psychological processing.

I came away from the MIT lecture disappointed by the indifference to the remarkable and important experimental results obtained both at Cambridge and in my laboratory, a disappointment that persisted as the feature approach to visual processing became overwhelmingly dominant during the 1990s.

## Feature Detection vs. Feature Extraction

Within the feature approach, two very different procedures can be followed. In one, the emphasis is on detecting some element in the sensory input, a bottom-up direction of inquiry; in the other, the feature is extracted from a myriad of sensory and cognitive processes in a top-down fashion. Extraction involves identification of the feature, essentially a creative process.

Different cells in the brain's visual cortex differ in their response to the orientation, to the velocity or to the acceleration of movement of a line. We, as visual creatures, can analyze any scene into lines and edges; however, the maps of the brain's receptive fields were initially interpreted not as analyzers of an entire vista but as brain cells that were "detecting" lines. A detector, as the word implies, needs to be uniquely sensitive to that which is being detected. A Geiger counter, fitted to detect radioactivity, would be useless if it were sensitive to everything in an environment including auditory noise, aromas, changes in visual brightness, or the contours of a shape.

The feature detection approach had an initial advantage in exploring form as Euclidian shapes. Maps of the receptive fields recorded from visual pathways yielded an "irresistible" progression: the maps change from a circular shape in the retina and the thalamus to an elongated shape at the cortex. An important aspect of the maps was that they were elicited only by stimuli of specific orientations (horizontal, vertical and all angles in between.) These oriented elongated shapes—interpreted as lines and edges—could then be considered to be a two-dimensional “stick-figure“ process representing features of our visual environment. But, as is well known, lines need not actually be present for us to perceive a shape.

*16. The Kaniza Triangle*

For example:

Contrary to what was becoming “established,” we showed in my laboratory that the supposed “Geiger counter” cells demonstrated sensitivities to many stimuli far beyond their sensitivity just to the presentation of lines. Some of these cells also responded to select bandwidths of auditory stimulation. All of them respond to changes in luminance (brightness), while other cells respond also to color. As described in Chapter 2, the Berkeley brain scientists Russell and Karen DeValois, on the basis of their decades-long experimental results, have constructed a model showing that the same network of cells can provide for our experience both of color and of form: When connected in one fashion, processing leads to the experience of form; when connected in another fashion, our experience is of color. The fact that a *single network can accomplish both* is important because we rarely experience color apart from form.

Perhaps more surprising was our finding that some of these cells in the primary visual sensory receiving cortex, when recorded in awake problem-solving monkeys, respond to whether the monkey’s response to a visual stimulus had been rewarded or not—and if so, whether the monkey had pressed one panel or the other in order to receive that reward.

## A Show of Hands

To illustrate how such a network might function, I ask the students in my class to do the following: "All those who are wearing blue jeans, please raise your hand. Look at the distribution of hands. Now lower them. Next, all those wearing glasses, please raise your hands. Look at the distribution of hands and note how different it is from the distribution produced by those wearing blue jeans." Again, "All girls, raise your hands; then all boys." We quickly observe that each distribution, each pattern, is different. The features—blue jeans, glasses, gender—were coded by the various patterns of raised hands, a *pattern* within a web, not by the characteristic of only a single individual person,

*Brain cells are like people when you get to know them.* Each is unique. All features are distributed among the group of individuals, but not all the individuals share all the features. Also, as in the saying "birds of a feather flock together," brain cells sharing the same grouping of features tend to form clusters. Thus, one cluster will have more cells that are sensitive to color; another cluster will have more cells that are sensitive to movement. Still, there is a great deal of overlap of features within any cluster. People are the same in many respects. For instance, some of us have more estrogen circulating in our bodies while others have more testosterone. But all of us have some of each.

With this arrangement of "features as patterns," the question immediately arises as to who asks the question as I did with my students: Who is wearing blue jeans? This question is known as an example of a *top-down* approach to processing, whereas feature detection is a *bottom-up* approach. In my laboratory, my colleagues and I spent the better part of three decades establishing the anatomy and physiology of the routes by which top-down processing occurs in the brain. Together with the results of other laboratories, we demonstrated that electrical stimulation of the sensory-specific "association" regions of the brain cortex changed the patterns of response of sensory receptors to a sensory input. Influence of such stimulation was also shown to affect all the "way stations" that the sensory input traversed en route to the sensory receiving cells in the cortex.

Even more surprising was the fact that the effects of an auditory or touch stimulus would reach the retina in about the same amount of time that it takes for a visual stimulus to be processed. Tongue in cheek, I've noted these results in the phrase: "We *live* in our sensory systems." The experimental findings open the important question as to where all our processing of sensory input begins, and what is the sequence of processing. That question will be addressed shortly and again in depth when we analyze frames and contexts.

## What Features Are Featured?

But meanwhile, to return for a moment to the notion of line detectors: the visual cortex cannot be processing straight lines or edges per se because the input from the retina is not received in the form of a straight line. As Leonardo da Vinci showed in the 15th century, the retina is a hemisphere. A perceived line must therefore be abstracted from a curve. When you fly from New York to London you travel via Newfoundland, Iceland and Greenland in an arc that describes the shortest distance between two points on the globe. On a sphere, the shortest distance on a globe is *not* a straight line. Riemann developed a geometry that applies to curved surfaces. The brain's visual processing, therefore, must operate according to Riemannian principle and must be based on Pythagorean arcs, angles and cones, not on the points and lines of Euclidian geometry. Experimental psychologist James Gibson and his students at Cornell University have taken this aspect of vision seriously, but their work needs to be incorporated by brain scientists in their account of visual sensory processing.

## A Symposium in the Roman Tradition

I was able to bring the attention of the neuroscience community to the issue raised during the encounter at MIT and to the spatial frequency formulation of visual receptive fields at a convention of the Society for Neuroscience held in Minneapolis (in the mid-1970s.) Mortimer Mishkin —a friend and former doctoral and postdoctoral student of mine during the 1950s—had, in his capacity of program chairman, asked me to organize a special symposium covering microelectrode studies in visual neuroscience. The symposium was to be special in that it would be held in the Roman tradition: the symposiasts arguing their respective views over flasks of wine!

The society was still of a manageable size (it has since grown to 36,000 members) and attendance at this particular symposium was restricted to an audience of 300. Wine and cheeses were served to all.

Symbolically (both from a political and a geographical standpoint) I placed Russell and Karen DeValois from the University of California at Berkeley to my left, and, to my right, Horace Barlow from Cambridge University and David Hubel from Harvard. Hubel, together with Torsten Wiesel, also of Harvard, had recently received the Nobel Prize for their work on "feature detection," and I was pleased that he had graciously consented to participate in what was meant to be a challenging session.

I asked David to go last in our series of presentations, hoping that, if allowed to imbibe enough wine, he would be sufficiently mellow to welcome a discussion of any disagreements with his views on the neural substrate of perception. My plan worked.

Russell and Karen DeValois presented their data, which provided solid evidence for a frequency description of the pattern of receptive fields in the visual cortex. They also presented critical evidence *against* the formulation that line or edge detection of shapes best describes those receptive fields. Horace Barlow then presented evidence for how groups of cells in the brain *extract* a feature from the multiple features that characterize a visual scene, as opposed to the view that any single brain cell responds solely and uniquely to a particular feature such as a line.

Finally, I introduced David Hubel. In my introduction, I noted three things:

1. that David was a modest person, who would claim that he hadn't understood the mathematical aspects of the DeValois presentation—but I would not let him get away with this because he had taught high school math before going to medical school;
2. that, in my experience, each cortical neuron encodes several features of our visual environment, that each neuron is like a person with many attributes, and thus our ability to recognize features had to depend on patterns displayed by groups of neurons for further processing;
3. that, as just presented, Karen and Russ DeValois had done critical experiments showing that the visual cortical cells *were tuned to spatial frequency rather than to the shapes of "lines" or "edges."*

Hubel immediately announced to the audience, "Karl is right in everything he says about cortical cells, but I have never seen anything like what Russell DeValois is talking about." Russ DeValois responded, "You are welcome to come to our laboratory at any time and see the evidence for yourself." Hubel replied, "But I wouldn't believe it if I saw it." I chimed in, "David I didn't realize you were a flatlander." The symposium was on.

Hubel went on to point out that although cells might respond to many inputs, he was convinced they responded more to what he called a "critical sensory stimulus." As a moderator I felt that I had said enough and didn't challenge him on this, but as demonstrated in my laboratory and in many others, although his statement is correct for the receptive fields in further processing stations, (where the so-called "grandmother cells" are located) this characterization is incorrect for receptive fields in the primary sensory receiving cortex.

Hubel did admit that his views on feature detection had received little confirmation over the decades since he had first proposed them, but the identification of so-called "grandmother" cells that responded especially well to higher-order configurations, such as hands and (grandmothers') faces, kept his faith in the feature detector view alive.

The audience and I felt amply rewarded by the exchange. Issues had been clearly engaged in a friendly and supportive fashion. This was science at its best.

Several issues had been aired. One, highlighted in Barlow's presentation, is, of course, that feature extraction —as described earlier in this chapter by the metaphor of a show of hands—is eminently plausible but should not be confused with feature detection.

A second issue, highlighted by the DeValoises, and explored in the next chapter—sensory processing— involves the frequency domain.

## Green Hand Cells

Finally, Hubel's faith in "grandmother cells" was well placed. As we proceed from the primary sensory receiving cortex to the temporal lobe of the brain, we find receptive fields that are "tuned" to an ever "higher order," that is, to ever more complex stimuli. The receptive fields of these "grandmother cells" are nodes in an assembly that is capable of representing features as higher-order properties abstracted from lower-order properties. Thus, we can come to understand how a property like "blue jeans" in the metaphor I've used can become abstracted from the population of persons who wear them. Sales counters at retail stores handle blue jeans; cells in the brain's temporal lobe respond to pictures of grandmother faces and other sensory images such as flowers and hands.

Cells responding primarily to pictures of hands were the first "grandmother cells" to be discovered. Charles Gross at Princeton University was the first to record them. I asked Gross, who had attended a course I was teaching at Harvard and as a consequence became a student of Larry Weiskrantz at Cambridge and Oxford, whether the face cells responded to stimuli other than faces. They did, but not as vigorously (as noted by Hubel in our symposium). However, in my laboratory, we unexpectedly found, in one monkey who'd had considerable experience choosing a green rather than a red set of stripes, that his cell's activity went wild when he was shown the combination as a green hand!

As had also been found by Gross, in experiments in my laboratory, we found that the amount of activity elicited from these "hand cells" was almost as great when we visually presented broad stripes to the monkey. We presented stripes because they could provide the basis for a frequency interpretation of how the cells might process a hand.

We can derive two important conclusions from the results of these experiments:

1. Higher-order processing locations in the brain enable us to make distinctions among complex stimuli.
2. Our ability to make such distinctions can be learned.

## Seeing Colors

James and Eleanor Gibson of Cornell University, using purely behavioral techniques, had also reached the conclusion that higher-order distinctions are learned. The Gibsons reported their results in a seminal publication in which they showed that perceptual learning is due to progressive differentiation of stimulus attributes, not by forming associations among them.

*Taking Matte Blanco's definition that our conscious experience is based on making distinctions, as described in the opening paragraphs of* *this chapter, this line of research indicates how our brain processes, through learning, make possible progressively greater reaches of conscious experience.*

The processes by which such distinctions are achieved were addressed at another meeting of the Society for Neuroscience—this one in Boston in the 1980s. Once again, David Hubel gave a splendid talk on how brain processes can entail progressively greater distinctions among colors. He noted that, as we go from receptor to visual cortex and beyond, a change occurs in the coordinates within which the colors are processed: that processing changes from three colors at the receptor to three opponent pairs of colors at the thalamus and then to six double-opponent pairs at the primary sensory cortex. Still higher levels of processing "look at the coordinates from an inside vantage" to make possible the experiencing of myriads of colors. A change in coordinates is a transformation, a change in the code by which the form is processed.

Transformations are the coin of making ever-greater distinctions, refinements in our conscious experience. After his presentation in Boston, I spoke with David Hubel and said that what he had just done for color was exactly what I was interested in doing for form. David said he didn't think it would work when it came to form. But of course it did. The prodigious accomplishments of the 1970s and 80s form the legacy of how visual angles at different orientations can become developed into a Pythagorean approach to visual pattern vision. (Hubel and I have never had the opportunity to discuss the issue further.)

## Form as Pattern

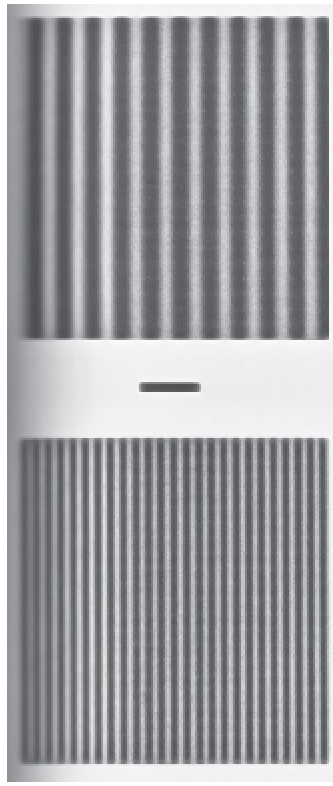
A different path of experimentation led me to explore the view of form as pattern. In my earlier research, while examining the effects of cortical removals on the behavior of monkeys, I had to extensively examine the range of responses to stimuli that were affected by removing a particular area of the brain cortex. Thus, during the 1960s, when I began to use micro-electrodes, I used not only a single line but two lines in my receptive field experiments. The *relationship* of the lines to one another could thus be explored. Meanwhile, other laboratories began to use multiple lines and I soon followed suit.

Multiple lines of different width and spacing (that is, stripes) produce a "flicker" when moving across the visual field. We experience such a flicker when driving along a tree-lined road: the rapid alternation of such light and shadow stripes can actually incite a seizure in seizure-prone people. The rapidity of the flicker, the speed of the alternation between light and dark can be described mathematically in terms of its *frequency*.

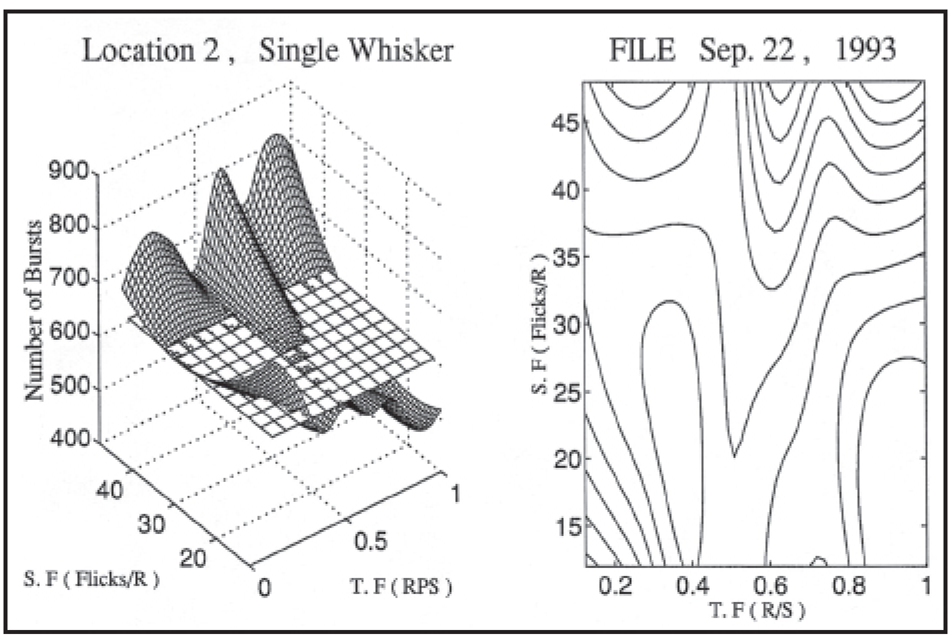
When we moved such stripes before the eye of a subject in our experiments, we could change the response of the subject's cortical receptive field by changing the frequency of the stimulation in two ways: by altering the speed at which we moved the stimulus, or by changing the width of the stripes and the spaces between them.

Mathematically, this relationship among the angles on the retina that result from stimulation by stripes is expressed as degrees of arc of the portion of a circle. A circle, as noted earlier, represents a cycle. Degrees of arc are measures of the density, the rapidity of oscillations between light and dark in the cycle. Thus, the oscillations are the spectral transform of the spatial widths of the alternating light and dark stripes. It follows that changes in the width of the light and dark stripes will change the frequency spectrum of the brain response.

Those of us who used multiple lines in our experiments have described our results in terms of "spatial frequency."Frequency over space as distinct from frequency over time can be demonstrated, for example, if we visually scan the multiple panels that form a picket fence or similar grating. When we visually scan the fence from left to right, each panel and each gap in the fence projects a pattern of alternating a bright region and a shadow region onto the curve of our retina. Therefore, each bright region and each shadow covers an angle of the curve of our retina. The "density" of angles is defined by how close the stimulating bright and dark regions (the width of the fence panels and their spacing) are to each other.



*17. Low- and High-Frequency Gratings*




*18. Receptive Field and Contours*

In our hearing, within the acoustical domain, we have long been accustomed to thinking in terms of the temporal frequency of a sound determining its pitch. In seeing, we now had demonstrated that a visual pattern, an image, is determined in the same fashion by its spatial frequency. “Wow! The eye works just like the ear.” This insight— *that all senses might function in a similar mode*—was a most dramatic revelation. My long-sought quest for a way to understand the processing of the visual as radiation, similar to the processing of color, was at last realized.

## Waves: A Caveat

In the early 1960s, when the holographic formulation of brain processes was first proposed, one of the main issues that had to be resolved was to identify the waves in the brain that constituted a hologram. It was not until I was writing this book that the issue became resolved for me. The short answer to the question as to what brainwaves are involved is that *there are none*.

For many years David Bohm had to chastise me for confounding waves with spectra, the results of interferences among waves. The transformation is between space-time and spectra. Waves occur in space-time as we have all experienced. Thus the work of Karen and Russell DeValois, Fergus Campbell and the rest of us did *not* deal with the frequency of waves but with the frequency of oscillations— the frequency of *oscillations* expressed as wavelets, as we shall see, between hyperpolarizations and depolarizations in the fine-fiber neuro-nodal web.

*Waves* are generated when the energy produced by oscillations is constrained as in a string—or at a beachfront or by the interface between wind and water. But the unconstrained oscillations do not produce waves. Tsunamis (more generally solitons) can be initiated on the east coast of Asia. Their energy is not constrained in space or time and so is spread over the entire Pacific Ocean; their effect is felt on the beaches of Hawaii. But there are no perceptible waves over the expanse of the Pacific Ocean in between. The oscillations that “carry” the energy can be experienced visually or kinesthetically, as at a beach beyond the breakers where the water makes the raft bob up and down in what is felt as a circular motion. In the brain, it is the constraints produced by sensory inputs or neuronal clocks that result in various frequencies of oscillations that we record in our ERPs and EEGs.

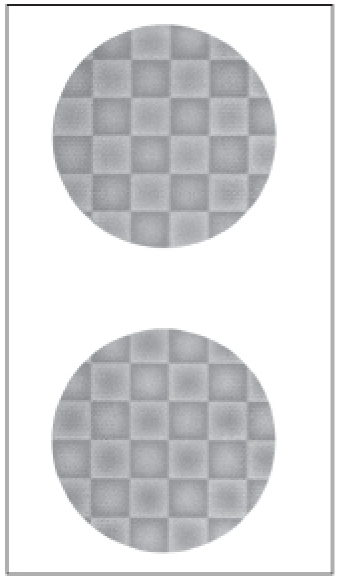
## Critical Tests

Fergus Campbell provided an interesting sidelight on harmonics, the relationships among frequencies. The test was critical to viewing the perception of visual form as patterns of oscillation. When we hear a passage of music, we hear a range of tones and their harmonics. A fundamental frequency of a tone is produced when a length of a string is plucked. When fractions of the whole length of the string also vibrate, harmonics of the fundamental frequency are produced. When we hear a passage of music, we hear the fundamental tones with all of their harmonics. Surprisingly, we also hear the fundamental tones when only their harmonics are present. This is called experiencing the "missing fundamental."

I was able to experience another exciting moment when in the 1970s I was visiting Cambridge, Fergus Campbell demonstrated that in vision, as in audition, we also experience the "missing fundamental." Yes, the eye is like the ear.

The results of two other sets of experiments are critical to demonstrating the power of the frequency approach to analyzing visual patterns. Russell and Karen DeValois and their students performed these experiments at the University of California at Berkeley. In one set, they mapped an elongated receptive field of a cortical neuron by moving a single line in a particular orientation across the visual field of a monkey's eye. (This form of mapping had been the basis of the earlier interpretation that cells showing such receptive fields were "line detectors.") The DeValoises went on to widen the line they presented to the monkey until it was no longer a line but was now a rectangle: The amount of the cell's response did not change! The cell that had been described as a line detector could not discriminate—could not resolve the difference—between a line and a rectangle.

In this same study, the experimenters next moved gratings with the same orientation as that of the single line across the visual field of the monkey. These gratings included a variety of bar widths and spacing (various spatial frequencies). Using these stimuli, they found that the receptive field of the cell was tuned to a limited bandwidth of spatial frequencies. Repeating the experiment, mapping different cortical cells, they found that different cells responded not only to different orientations of a stimulus, as had been found previously, but that they were tuned to different spatial frequencies: the ensemble of cortical cells had failed to discriminate between a line and a rectangle but had excellent resolving power in distinguishing between band widths of frequencies.

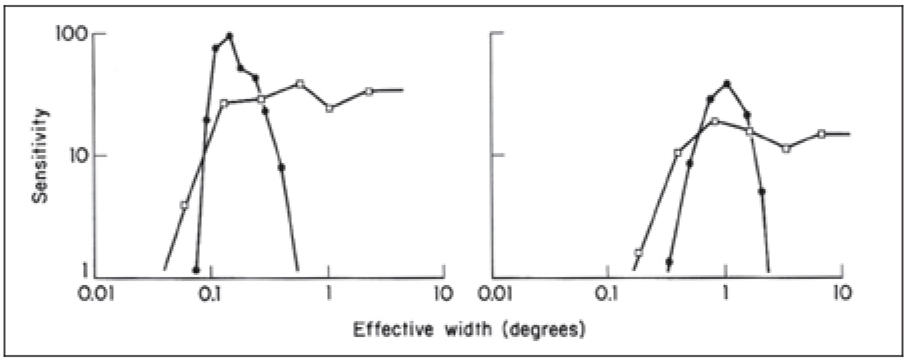


*19. The missing fundamental: note that the patterns do not change: the bottom, as you view it, is the pattern formed with the fundamental missing*

For the second set of experiments the DeValoises elicited a receptive field by moving a set of parallel lines (a grating) across the monkey's receptive field. As noted earlier, one of the characteristics of such fields is their specificity to the orientation of the stimulus: a change in the orientation of the lines will engage other cells, but the original cell becomes unresponsive when the orientation of the grating is changed.

Following their identification of the orientation selectivity of the cell, the DeValoises changed their original stimulus to a plaid. The pattern of the original parallel lines was now crossed by perpendicular lines. According to the line detector view, the cell should still be "detecting" the original lines, since they were still present in their original orientation. But the cell no longer responded as it had done. To activate the cell, the plaid had to be rotated.

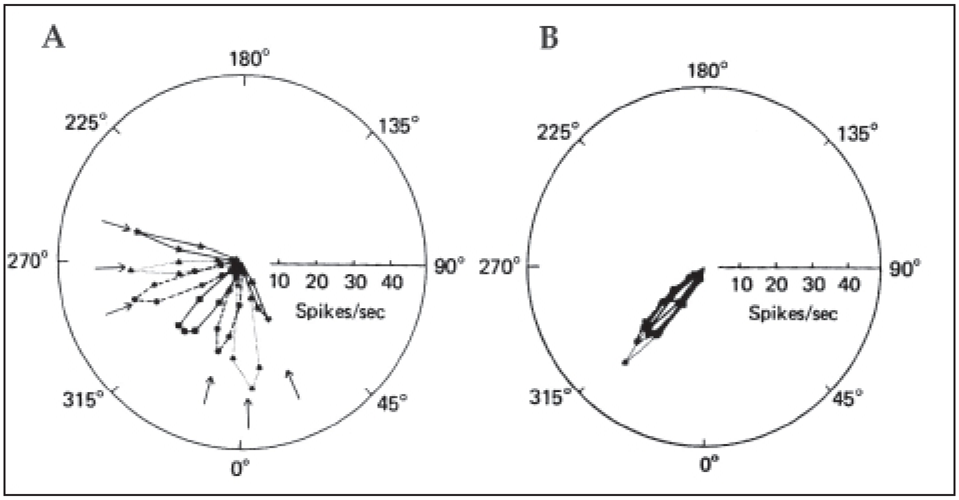
The experimenters predicted the amount of rotation necessary to activate the cell by scanning each plaid pattern, then performing a frequency transform on the scan using a computer program. *Each cell was responding to the frequency transform of the plaid that activated it, not detecting the individual lines making up the plaid.* Forty-four experiments were performed, and in 42 of them the predicted amount of, rotation came within two minutes of arc; in the other two experiments the results came within one degree of predicting the amount of rotation necessary to make the cell respond. Russell DeValois, a rather cautious and reserved person, stated in presenting these data at the meeting of the American Psychological Association that he had never before had such a clear experimental result. I was delighted.




*20. Tuning functions for two representative striate cortex cells. Plotted are the sensitivity functions for bars of various widths (squares) and sinusoidal gratings of various spatial frequencies (circles). Note that both cells are much more narrowly tuned for grating frequency than for bar width. (From Albrecht et al., 1980, copyright 1980, AAAS. Reprinted by permission.)*

## Signs of the Times

An excellent example of the strengths and limitations of currently accepted views regarding the feature detection versus the frequency views is provided by a *Scientific American* article (April 2007) entitled “The Movies in Our Eyes,” authored by Frank Werblin and Botond Roska. The article describes a series of elegant experiments performed by the authors, who recorded the electrical activity of ganglion cells of the retina of rabbits. It is the ganglion cells that give rise to the axons that relay to the brain the patterns developed during retinal processing of radiant energy. The authors had first classified the ganglion cells into 12 categories depending on their receptive fields, their dendritic connections to earlier retinal processing stages. These connections were demonstrated by injecting a yellow dye that rapidly spread back through all of the dendrites of the individual ganglion cell under investigation.




*21. Orientation tuning of a cat simple cell to a grating (squares and solid lines) and to checkerboards of various length/width ratios. In A the responses are plotted as a function of the edge orientation; in B as a function of the orientation of the Fourier fundamental of each pattern. It can be seen that the Fourier fundamental but not the edge orientation specifies the cell's orientation tuning (From K. K. DeValois et al., 1979. Reprinted with permission.)*

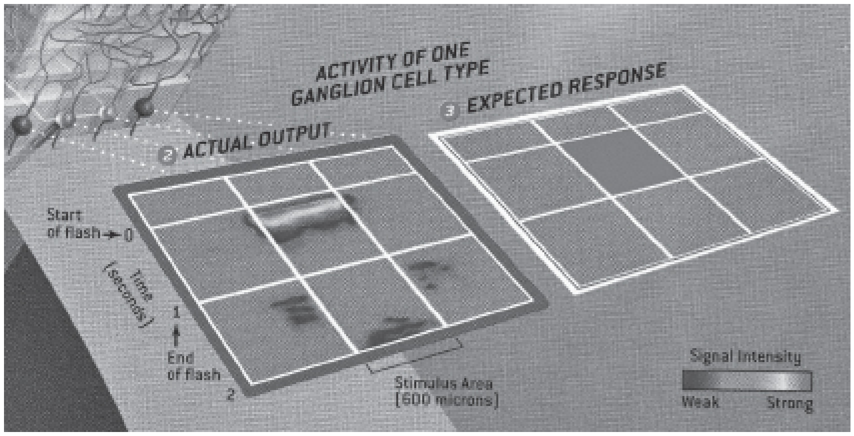
The authors recorded the patterns of signals generated in each of the different types of ganglion cell by a luminous square and also by the presentation of a frame of one of the author's illuminated faces. They then took the resulting patterns and programmed them into an artificial neural network where they were combined by superposition. The resulting simulation was briefly (for a few milliseconds) displayed as an example of a retinal process, a frame of a movie, sent to the brain. In sequence, the movies showed a somewhat fuzzy depiction of the experimenter's face and how it changed as the experimenter talked for a minute.

In their interpretation, the experimenters emphasized the spatial aspect of the representation of the face and the time taken to sequence the movies. They also emphasize the finding that the retina does a good deal of preprocessing before it sends a series of partial representations of the photic input to the brain for interpretation: "It could be that the movies serve simply as elementary clues, a kind of scaffolding upon which the brain imposes constructs" (p. 74). Further: " . . . the paper thin neural tissue at the back of the eye is already parsing the visual world into a dozen discrete components. These components travel, intact and separately, to distinct visual brain regions—some conscious, some not. The challenge to neuroscience now is to understand how the brain interprets these packets of information to generate a magnificent, seamless view of reality" (p. 79).

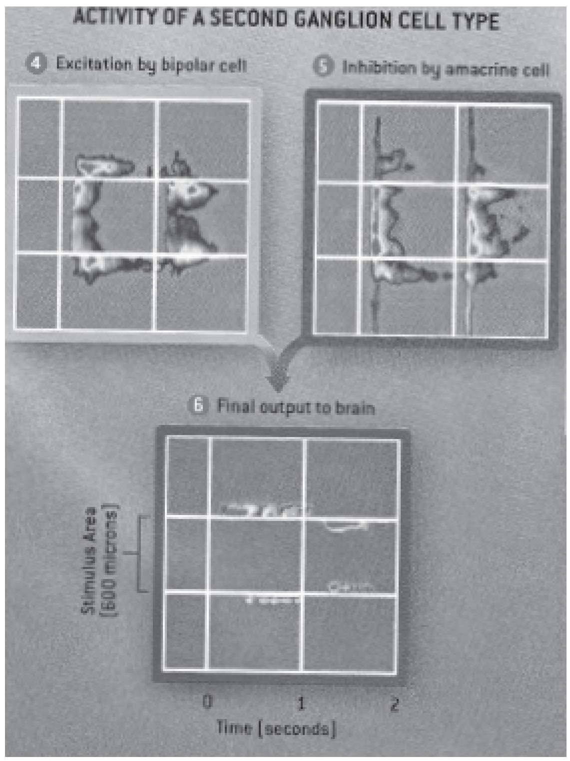
However, the authors ignore a mother lode of evidence in their own findings. The electrical activity, both excitatory and inhibitory, that they record from the ganglion cells, even from the presentation of a square, show up as wavelets! This is not surprising since the input to the ganglion cells is essentially devoid of nerve impulses, being mediated only by way of the fine-fiber neuro-nodal web of the prior stages of processing—a fact that is not mentioned in the *Scientific American* paper. Wavelets are constrained spectral representations. Commonly, in quantum physics, in communication theory and in neuroscience the constraint is formed in space-time. Thus, we have Gabor's quanta of information.

Werblin and Roska speak of "packets of information" but do not specify whether these are packets of scientifically defined (Shannon) information or a more loosely formulated concept. They assume that the space-time "master movie" produced by the retinal process "is what the brain receives." But this cannot be the whole story because a considerable amount of evidence has shown that cutting all but any 2% of the optic nerve does not disturb an animal's response to a visual stimulus. There is no way that such an ordinary master movie could be contained as such in just 2% of any portion of the optic tract and simply repeated in the other 98%. Some sort of compression and replication has to be involved.

Given these observations on Werblin and Roska's experimental results and the limitations of their interpretations, their presentation can serve as a major contribution to the spectral view of visual processing as well as the authors' own interpretation in terms of a feature view. The spectral aspect of their data that they ignore is what is needed to fill out their feature scaffolding to form what they require to compose the seamless view of the world we navigate.




*22. The Retinal Response to a Rectangle*



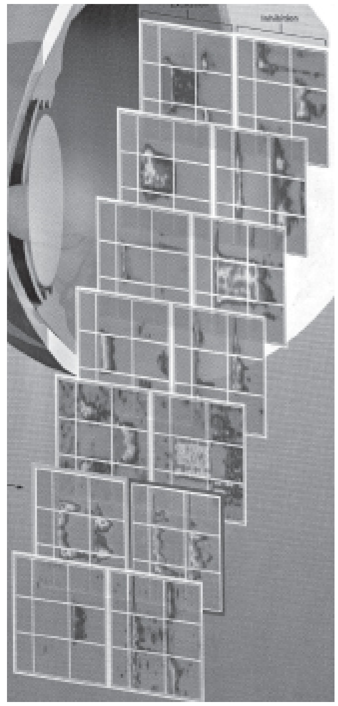

*23. Activity of a Second Ganglion Cell Type*

# Revisiting Geometry and Trigonometry

The strengths and weaknesses of the feature and the frequency (spectral) views of brain processes in perception provide a fresh look at the way science works. The experiments that led to the feature view showed the importance of the orientation of the stimulus. The experiments upon which the frequency view is based showed that the cortical cells were not detectors of stimulus “elements” but were responsive to interrelations among them. Furthermore, the frequency approach demonstrated that the power and richness of a spectral harmonic analysis could enable a full understanding of neural processing in perception. Unfortunately, those holding to the feature approach have tended to ignore and/or castigate the frequency approach and the results of its experiments. There is no need to exclude one or the other approach because the results of harmonic analysis can be translated into statistics that deal with features such as points; and into vectors that deal with features such as oriented lines.

There is a good argument for the ready acceptance of the feature detection approach. It is simple and fits with what we learned when taking plane geometry in high school. But the rules of plane geometry hold only for flat surfaces, and the geometry of the eye is not flat. Also, the rules of plane geometry hold only for medium distances, as a look at the meeting of parallel railroad tracks quickly informs us. A more basic issue has endeared brain scientists to the feature detection approach they have taken: the rules of plane geometry begin with points, and 20th century science insisted on treating events as points and with the statistical properties of combinations of points which can be represented by vectors and matrices. The frequency approach, on the other hand, is based on the concept of fields, which had been a treasured discovery of the 19th century.

David Marr, Professor of Computational Science at MIT, was a strong supporter of the feature view. But he could not take his simulations beyond two dimensions— or perhaps two and a half dimensions. Before his untimely death from leukemia, he began to wonder whether the feature detector approach had misled him and noted that the discovery of a cell that responded to a hand did not lead to any understanding of process. All the discovery did was shift the scale of hand recognition from the organism to the organ, the brain.

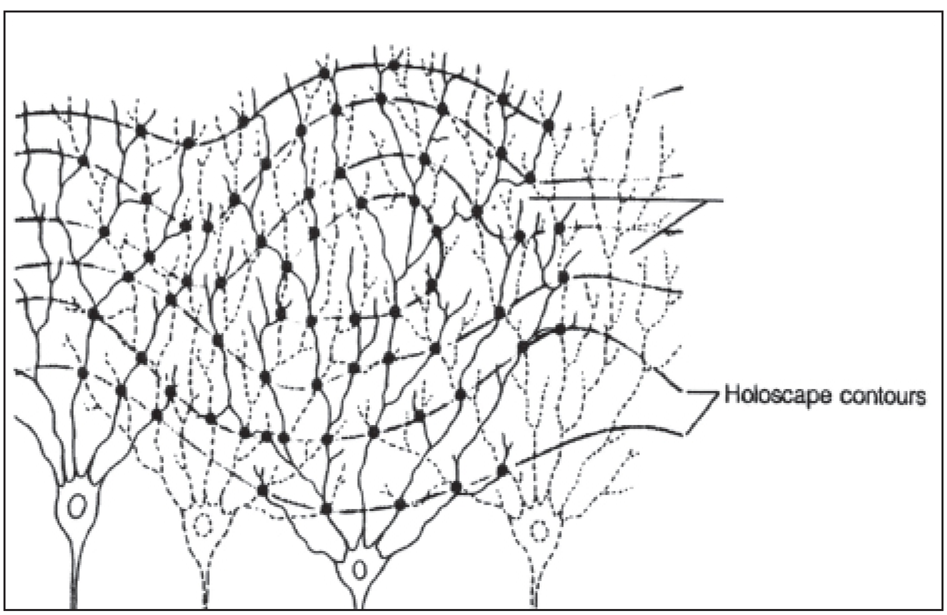


*24. The Receptive Fields of Seven Ganglion Cell Types Arranged Serially*

As I was writing the paragraphs of this chapter, it occurred to me that the resolution to the feature/frequency issue rests on the distinction between research that addresses the structure of circuits vs. research that addresses processes at the deeper neuro-nodal level of the fine-fibered web. The circuits that characterize the visual system consist of parallel channels, the several channels conveying different patterns of signals, different features of the retinal process. (My colleagues and I identified the properties of x and y visual channels that reach the cortex as identical to the properties of simple and complex cortical cells.) Thus, feature extraction, the creative process of identifying features, can be readily supported.

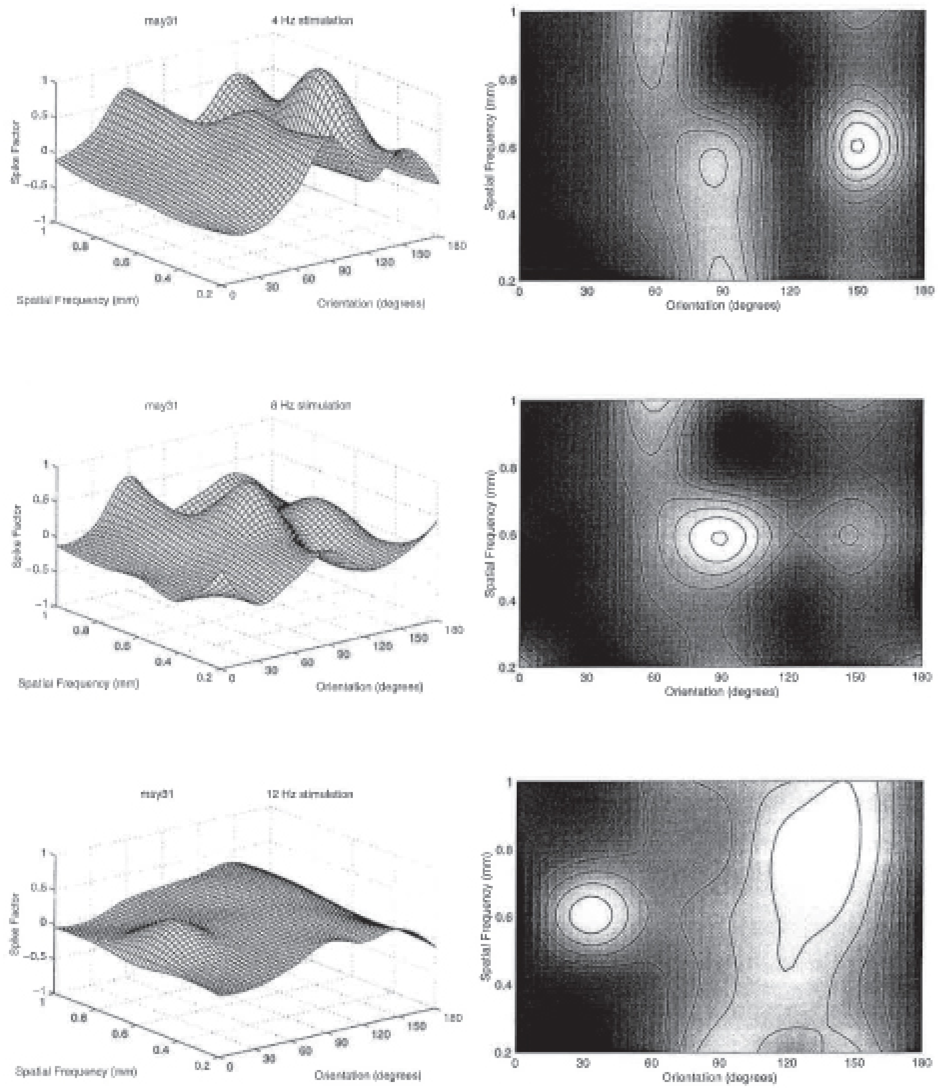
The frequency approach uses the signals recorded from axons to map the processes going on in the fine- fibered dendritic receptive fields of those axons. This process can generate features as they are recorded from axons. Taking the frequency approach does not require a non-quantitative representation of the dendritic receptive fields, the holoscape of the neuro-nodal process. Holoscapes can be quantitatively described just as can landscapes or weather patterns. The issue was already faced in quantum physics, where field equations were pitted against vector matrices during the early part of the 20th century. Werner Heisenberg formulated a comprehensive vector matrix theory and Erwin Schrödinger formulated a comprehensive set of wave functions to organize what had been discovered. There was a good deal of controversy as to which formulation was the proper one. Schrödinger felt that his formulation had greater representational validity (*Anschaulichkeit*). Heisenberg, as was Niels Bohr, was more interested in the multiple uses to which the formulation could be put, an interest that later became known as the Copenhagen implementation of quantum theory which has been criticized as being conceptually vacant. Schrödinger continued to defend the conceptual richness of his approach, which Einstein shared. Finally, to his great relief, Schrödinger was able to show that the matrix and wave equations were convertible, one into the other.

I shared Schrödinger's feeling of relief when, three quarters of a century later, I was able to demonstrate how to convert a harmonic description to a vector description using microelectrode recordings taken from rats' cortical cells while their whiskers were being stimulated. My colleagues and I showed (in the journal *Forma,* 2004) how vector representations could be derived from the waveforms of the receptive fields we had plotted; but showed that the vector representation, though more generally applicable, was considerably impoverished in showing the complexity of what we were recording, when compared with the surface distributions and contour maps from which the vectors were extracted.



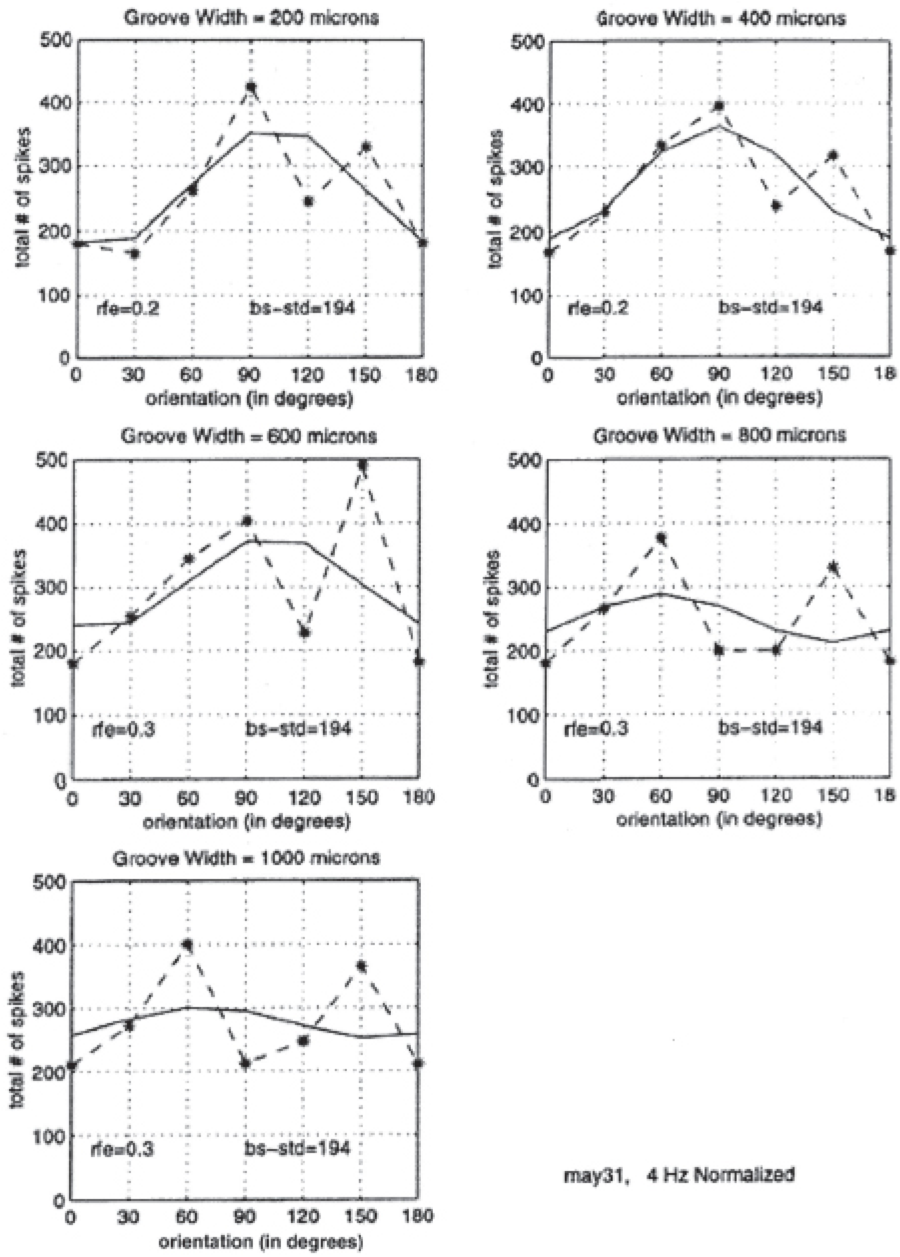

*25. The Holoscape*

## Receptive Field and Contour Maps

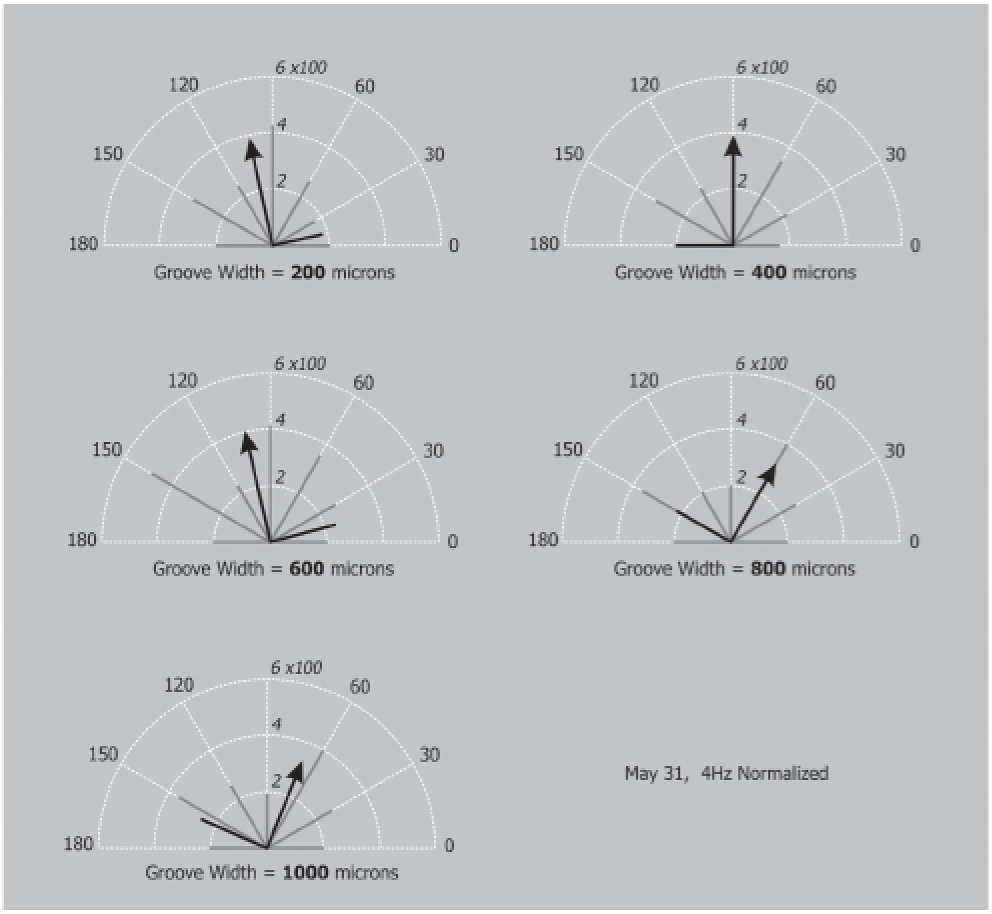



*26. An example for the three-dimensional representation of the surface distribution and associated contour map of the electrical response to buccal nerve stimulation. The surface distributions were derived by a cubic interpolation (spline) procedure. The contour maps were abstracted from the surface distributions by plotting contours in terms of equal numbers of spikes per recording interval (100 msec). The buccal nerve stimulation whisked the rat's whiskers against teflon discs whose textures (groove widths that determined the spatial frequency of the disc) varied from 200 to 1000 microns and whose grooves were oriented from 0 to 180 degrees. Separate plots are shown for each frequency of buccal nerve stimulation: 4Hz, 8Hz, and 12 Hz (top to bottom).*

Sinusoids Abstracted from Contours
Representation of Cortical Unit Response to Texture and Orientation of Tactile Gratings




*27. The cosine regressions of the total number of spikes for the orientation of the stimulus for the 4 Hz condition are shown.*




*28. Vectors*

The use of both the harmonic and the vector descriptions of our data reflect the difference between visualizing the deep and surface structures of brain processing. Harmonic descriptions richly demonstrate the holoscape of receptive field properties, then patches—the nodes—that make up the neuro-nodal web of small-fibered processing. The vector descriptions of our data describe the sampling by large-fibered axons of the deep process.

# In Summary

The feature detection approach to studying how our brain physiology enables our perceptions, outlines a Euclidian domain to be explored. This approach, though initially exciting to the neuroscience community, has been shown wanting: research in my laboratory and that of others showed that the receptive fields of cells in the brain's visual cortex are not limited to detecting one or another sensory stimulus.

Instead, research in my laboratory, and that of others, showed that a feature, relevant to a particular situation, is identified by being extracted from a set of available features.

The frequency approach, based on recording the spectral dimensions of arcs of excitation subtended over the curvature of the retina, is essentially Pythagorean. Deeper insights into complex processing are obtained, insights that can provide the basis for identifying features.

Neither approach discerns the objects that populate the world we navigate, the subject of Chapter 6.

# Navigating Our World

# Chapter 5
## From Receptor to Cortex and Back Again

Wherein I trace the transformation of perceived patterns as they influence the brain cortex and as the brain cortex influences them.

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*If you throw two small stones at the same time on a sheet of motionless water at some distance from each other, you will observe that around the two percussions numerous separate circles are formed; these will meet as they increase in size and then penetrate and intersect each other, all the while retaining as their respective centers the spots struck by the stones. And the reason for this is that the water, though apparently moving, does not leave its original position. . . . [This] can be described as a tremor rather than a movement. In order to understand better what I mean, watch the blades of straw that because of their lightness float on the water, and observe how they do not depart from their original positions in spite of the waves underneath them*

*Just as the stone thrown in the water becomes the center and causes various circles, sound spreads in circles in the air. Thus every body placed in the luminous air spreads out in circles and fills the surrounding space with infinite likeness of itself and appears all in all and all in every part.*

—Leonardo da Vinci, *Optics*

*Enough has now been said to prove the general law of perception, which is this, that whilst part of what we perceive comes through our senses from the objects before us another* *part (and it may be the larger part) always comes out of our own head.*

—William James, *Principles of Psychology,* 1890

## Lenses: How Do We Come to Know What Is Out There?

In the early 1980s the quantum physicist David Bohm pointed out that if humankind did not have telescopes with lenses, the universe would appear to us as a holographic blur, an emptiness of all forms such as objects. Only recently have cosmologists begun to arrive at a similar view. String theoreticians, the mathematician Roger Penrose and Stephen Hawking (e.g., in *A Universe in a Nutshell)* have, for their own reasons, begun to suspect that Bohm was correct, at least for exploring and explaining what we can about the microstructure of the universe at its origin and horizon. But the horizon itself is still a spatial concept, whereas Bohm had disposed of space entirely as a concept in his lens-less order.

With respect to the brain, I have extended Bohm's insight to point out that, were it not for the lenses of our eyes and similar lens-like properties of our other senses, the world within which we navigate would appear to us as if we were in a dense fog—a holographic blur, an emptiness within which all form seems to have disappeared. As mentioned in Chapter 2, we have a great deal of trouble envisioning such a situation, which was discovered mathematically in 1948 by Dennis Gabor in his effort to enhance the resolution of electron microscopy. Today, thanks to the pioneering work of Emmet Leith in the early 1960s, we now have a palpable realization of the holographic process using laser optics.

## Holography

Leith's procedure was to shine a beam of coherent (laser) light through a half-silvered angled mirror that allowed some of the beam to pass straight through the mirror, and some of it to be reflected from its surface. The reflected portion of the laser light was beamed at right angles to become patterned by an object. The reflected and transmitted beams were then collected on a photographic plate, forming a spectrum made by the intersections of the two beams. Wherever these intersections occur, their amplitudes (heights) are either reinforced or diminished depending on the patterns "encoded" in the beams. A simple model of the intersections of the beams can be visualized as being very much like the intersections of two sets of circular waves made by dropping two pebbles in a pond, as described by Leonardo da Vinci.

When captured on film, the holographic process has several important characteristics that help us understand sensory processing and the reconstruction of our experience from memory. First, when we shine one of the two beams onto the holographic film, the patterns "encoded" in the other beam can be reconstructed. Thus, when one of the beams has been reflected from an object, that object can again be viewed. If both beams are reflected from objects, the image of either object can be retrieved when we illuminate the other.

An additional feature of holography is that one can retrievably store huge amounts of data on film simply by repeating the process with slight changes in the angle of the beams or the frequency of their waves (much as when one changes channels on a television set). The entire contents of the Library of Congress can be stored in 1 cubic centimeter in this manner.

Shortly after my inauguration to Emmet Leith's demonstration of holography, I was invited to a physics meeting held in a Buddhist enclave in the San Francisco Bay area. I had noted that the only processing feature that all perceptual scientists found to be non-controversial was that the biconcave lens of the eye performed a Fourier transform on the radiant energy being processed. Jeffrey Chew, director of the Department of Physics at the University of California at Berkeley, began the conference with a tutorial on the Fourier relationship and its importance in quantum physics. He stated that any space-time pattern that we observe can be transformed into spectra that are composed of the intersections among waveforms differing in frequency, amplitude, and their relation to one another, much as Leonardo Da Vinci had observed.

My appetite for understanding the Fourier transformation was whetted and became amply rewarded.

## Fourier's Discovery

Jean Baptiste Joseph Fourier, a mathematical physicist working at the beginning of the 19th century, did an extensive study of heat, that is, radiation below the infrared part of the visible spectrum. The subject had military significance (and thus support) because it was known that various patterns of heat could differently affect the bore of a cannon. Shortly thereafter, the field of inquiry called "thermo-dynamics" became established to measure the dissipation of heat from steam engines: the amount of work, and the efficiency (the amount of work minus the dissipation in heat) with which an engine did the work would soon be major interests for engineers and physicists. The invention of various scales that we now know as "thermo-meters"—Fahrenheit, Celsius and Kelvin—resulted, but what interested Fourier was a way to measure not only the amount of heat but rather to measure the spectrum of heat. The technique he came up with has been discovered repeatedly, only to have slipped away to be rediscovered again in a different context. We met this technique when we discussed the Pythagoreans, but both Fourier and I had to rediscover it for ourselves. The technique is simple, but if Fourier and other French mathematicians had difficulty with it, it may take a bit of patience on your part to understand it.

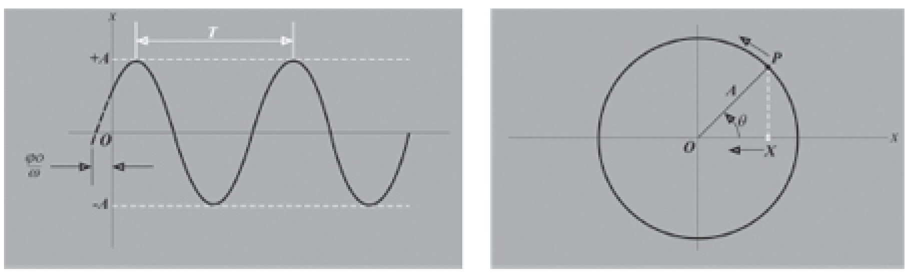
What is involved is looking at spectra in two very different ways: as the intersection among wave fronts and as mapped into a recurring circle.

To analyze the spectrum that makes up white light, we use a prism. What Fourier came up with to analyze the spectrum of heat can be thought of as analyzing spectra with a "clock." The oscillations of molecules that form heat can be displayed in two ways: 1) an up-and-down motion (a wave) extended over space and time, or 2) a motion that goes round and round in a circle as on a clockface that keeps track of the daily cycle of light and darkness.

Fourier, as a mathematician, realized that he could specify any point on a circle trigonometrically, that is by triangulating it. Thus he could specify any point on the circumference of the circle, that is, any point on an oscillation by its sine and cosine components. The internal angle of the triangle that specifies the point is designated by the cosine; the external angle, by the sine.

When he plotted these sine and cosine components on the continuous up-and-down motion extended over space and time, the sine wave and the cosine wave are displaced from one another by half a cycle. Where the two waveforms intersect, those points of intersection are points of interference (reinforcement or diminution of the height of oscillations) just as at the intersection of Leonardo's waves created by pebbles dropped into a pool. The heights of the points of intersection are numbers that can be used to calculate relations between the oscillations making up the spectra of heat. In this manner Fourier digitized an analogue signal.

Thinking back and forth between the two ways by which waveforms can be plotted is not easy. It took Fourier, a brilliant mathematician, several decades to work out the problem of how to represent the measure of heat in these two ways. One of my “happier times” was reading, in the original French and in English translations, Fourier’s stepwise groping toward this solution. My reason for being so happy was that I had tried for myself to understand his solution for over a decade and found not only that my solution was correct, but that Fourier had gone through the steps toward the solution much as I had. Further, I have just learned that quantum physicists are rediscovering this analytic “trick”: they speak of “modular operators” which divide the processes under investigation into clock-like repetitious segments. I asked my colleagues, “Like Fourier?” and received a nod and smile: I had understood.




*29. Representing Oscillations as Waveforms and as Circular Forms*

Meanwhile, as he was also active in politics during a most turbulent period in French history, Fourier had been put in jail and released several times before being appointed head of a prefecture. When Napoleon came to power, he soon recognized Fourier’s genius and took him to Egypt. Although French mathematics was the best in Europe, something might still be learned from the Arabs, whose mathematics had flowered some thousand years earlier.

## Fourier the Man

In addition to being given the opportunity to learn something about Arab mathematics firsthand, Fourier was put in charge of recording and describing Egyptian cultural artifacts for the expedition; he and his team made sketches of the architecture, sculpture and painting. In many instances, these sketches remain the only record we have of Egyptian monuments that have subsequently been destroyed. Fourier spent the rest of his life preparing these sketches for publication and providing financial and intellectual support for young Egyptologists such as his protégé Champollion, famed for deciphering Egyptian hieroglyphics by using the Rosetta stone (brought back to Europe by the same expedition).

On his return to Paris, Fourier first presented his "Analytic Theory of Heat" that had attained some maturity during his tour in Egypt. Within two weeks of this presentation, Laplace countered with a refutation showing that Fourier had not worked out an acceptable proof of his theoretical formulation. Laplace was correct in his critique of Fourier's proof: it took many years before a plausible proof was worked out. But the overriding importance of the tool that Fourier had devised for the measurement of the spectrum of heat made it possible for him to continue his mathematical explorations.

Fourier persisted. He had been appointed head of his local prefecture and paid for the publication of his fur- ther work using the salary of his office. Meanwhile, a great many scientists and engineers were using his technique to solve their problems in a variety of disciplines. After a decade, when Fourier was awarded a prestigious prize, Laplace began to support the publication of his work and his election to the French Academy of Sciences.

Over nearly two centuries, Fourier's theorem has become widely regarded as a most useful formula for measuring and predicting recurring patterns—from those characterizing bull and bear markets in the stock exchange to possible meltdowns in nuclear reactors. Richard Feynman, the noted Nobel laureate in physics, stated in his lectures (Feynman, Leighton and Sands, 1963) that Fourier's theorem is probably the most far-reaching principle of mathematical physics.

As expressed by my colleagues at the University of California at Berkeley, professors of physiology Russell and Karen DeValois, there is every reason to expect this over-arching formulation to also play a key role in how we can understand sensory processes: "Linear systems analysis originated in a striking mathematical discovery by a French Physicist, Baron Jean Fourier, in 1822 . . . [, which] has found wide application in physics and engineering for a century and a half. It has also served as the principal basis for understanding hearing since its application to audition by Ohm (1843) and Helmholtz (1877). The successful application of these procedures to the study of visual processes has come only in the last two decades" (DeValois and DeValois, *Spatial Vision,* 1988).

## FFT: The Fast Fourier Transform

The mathematical technique that Fourier developed was published in final form in 1822 as *Théorie Analytique de la Chaleur* (*Analytical Theory of Heat*). Today, the once- controversial formula is the basis of the theory known as the "Fourier series"—and with its inverse, the "Fourier transformation"—provides a method whereby we can reduce any perceived configuration, any pattern, no matter how complex, into a series of numbers representing intersections among waveforms. Further, any such series can be restored to its original configuration by performing the transform again, using its inverse.

What Fourier's method provides us so beautifully is the ability to decompose a configuration, as we experience it, into a series of component parts. For instance, the first component might take in a broad sweep of a scene, of a sound, or of an EEG, and describe it by a low frequency. The next component may then focus on somewhat narrower aspects of the same configuration, and describe it by a somewhat higher frequency. Each subsequent component resolves the pattern into higher and higher frequencies. A series of a dozen components usually succeeds in representing the experienced space-time configuration in sufficiently fine grain to restore it faithfully when the inverse transform is performed. (Recall that performing a Fourier transformation twice returns the original configuration.) The successive components in the Fourier equation accomplish an increasing resolution, providing a finer grain, such as texture, to the configuration.

Fourier's pioneering method has led to many modifications of his insight, modifications that are grouped under the heading of orthogonal transformations, that is, transformations whose components do not interact with each other. In addition, non-linear modifications have been devised, such as that developed by Norbert Wiener, professor of mathematics at the Massachusetts Institute of Technology, for analyzing the EEG.

Furthermore, the goal of analyzing patterns into a series of component parts can now be accomplished by statistics in which each component in the series is represented by an "order." Fourth order (that is four terms in the series) must be used to reach the resolution necessary to represent a line or the texture of a visual scene. Statistics, based on enumerating items or things, are usually relatively easy to manipulate in calculations. Thus, statistical techniques are taught to every student who aspires to use or to understand the fruits of scientific enterprise. However, there are drawbacks to the teaching of statistics to the exclusion of other analytical techniques: in the next chapter I discuss how statistical analysis hides the forms behind the manipulations, the symmetries better understood in spectral terms.

This deeper understanding is one reason why frequency aficionados continue to tout the spectral domain. In addition, there is a most useful practical application: transforming into the spectral domain (and back out again) makes the computation of correlations, the basis of "imaging," simpler, whether by brain or computer. (The procedure uses "convolution," a form of multiplication of the spectral transformations of what needs to be correlated.)

I remember how we cheered the achievement of a computer program that would perform the Fourier transformation, the Fast Fourier Transform (FFT), while I was at the Center for Advanced Studies in the Behavioral Sciences at Stanford, California, in 1958–59. As a result, its use has become commonplace in medical image processing as in PET (positron emission tomography) scans and fMRI (functional Magnetic Resonance Imaging.) These successes raise the question: Might biological sensory functions also be based on spectral image processing? The next sections show that, not only can the Fourier theorem be usefully applied, but that its application resolves some longstanding problems in the understanding of the neurobiology of visual perception.

## A Retinal Image?

James Gibson, renowned for his work on sensory perception at Cornell University, was adamant in his rejection of the widely accepted notion that an image of a scene is displayed on the retina by the optics of the eye, a view taken seriously by most scientists. This view suggests that the eye is like a classical camera that is constructed so that the lens sharply focuses the scene onto the film to produce a two-dimensional spatial image. The retina is conceived to be like the film in the camera.

This analogy would mean that our three-dimensional perceptual experience must be constructed from this two-dimensional “retinal image.”

Gibson pointed out that this conception is faulty if only because there is constant movement in the relation between our eyes and the scene before us. His students also regarded as significant the hemispheric shape of our retina: their sophisticated view is that retinal excitation is described by cones of the Riemannian geometry of curved space, not by Euclidian points and lines. So why hasn’t their view been more generally accepted?

For me, the problem arose because, while at the University of Chicago, I had seen a retinal image, an image that appeared on the retina of the eye of an ox. Still, I felt that the Gibsonians were on to something important in placing their emphasis on (Pythagorean three-dimensional triangular) cones of light subtending degrees of arc on the retina. My discussions with Gibson did not help to solve the problem, because he insisted that all of the “information” (that is, the multidimensional patterns) was already there in the scene, and all the brain’s visual system needed to do was to “resonate” to that information. I agreed in principle but argued that we needed to know “the particular go” of how such resonances would become established. Gibson had proposed a relational, ecological approach to studying the information contained in the scene before us; I countered that we need an internal as well as an external ecology to explain the visual processing of the scene. Whenever I tried to bring brain facts into the discussion, Gibson laughed and turned off his hearing aid. I accused him of being the radical behaviorist of perception. It was all great fun, but did not resolve the issue.

## The Aha Experience

Resolution of the question “Is there a retinal image?” came in a flash while I was crossing a busy street in Edmonton. I had been asked to present the MacEachron lectures at the University of Alberta, Canada, lectures which were subsequently (1991) published as a book, *Brain and Perception*. The fourth lecture concerned processing by the optical structures of the eye. I had explained to my audience that the lens of the eye performs a Fourier transform: on one side of our lens is a space-time image as we experience it; on the other side of the lens is a holographic-like spectral distribution. If indeed there is a space-time retinal image, as I had seen in the ox eye, the input to the eye must be spectral. This explanation fit nicely with David Bohm's physics: as I mentioned earlier, Bohm had noted that if we did not have lenses, the universe would appear to us as a hologram.

However, Gibson's intuition regarding a retinal image, and my uncertainty about it, remained unresolved. As my hosts and I were crossing a very busy street after the lecture, discussing the issue, the answer suddenly became clear and we stopped short in the middle of the street: The retina is not a film. The retina is a multilayered structure that is sensitive to single quanta, photons of visible radiation. Quantum properties are multidimensional. Gibson may have been wrong in emphasizing the idea that there is no image at all, but he was correct in his intuition regarding visual processing as multidimensional from the start.

The optical image is, as Gibson pointed out, actually an optical flow. In addition, the image is somewhat "blurred," diffracted due to the gelatinous properties of the lens of the eye. (Technically, this blurring is called an "Airy disk.") Thus the optical image that appears at the surface of the retina is somewhat spectral in configuration. The retinal quantum process completes the transformation into the spectral domain.

Separating the optical image (or flow, the moving image) from the retinal quantum process is in tune with Gibson's intuition, which can now be developed in its entirety as follows:

a. Radiant energy (such as light and heat) becomes scattered, spectral and holographic, as it is reflected from and refracted by objects in the universe.
b. The input to our eyes is (in)formed by this spectral, holographic radiant energy.
c. The optics of our eyes (pupil and lens) then perform a Fourier transformation to produce a space-time flow, a moving optical image much as we experience it.
d. At the retina, the beginning of another transformation occurs: the space-time optical image, having been somewhat diffracted by the gelatinous composition of the lens, becomes re-transformed into a quantum-like multidimensional process that is transmitted to the brain.

## Gabor's Quantum of Information

The processes of the retinal transformation, and those that follow, are not accurately described by the Fourier equation. I discussed this issue with Dennis Gabor over a lovely dinner in Paris one evening, and he was skeptical of thinking of the brain process solely in Fourier terms: "It is something like the Fourier but not quite." At the time, Gabor was excited about showing how the Fourier transform could be approached in stages. (I would use his insights later in describing the stages of visual processing from retina to cortex.) But Gabor could not give a precise answer to why it was not quite how the brain process worked.

Gabor actually did have the answer—but he must have forgotten it or felt that it did not apply to brain processing. I found, after several years' search, that the answer "to not quite a Fourier" had been given by Gabor himself when I discovered that J. C. R. Licklider, then at the Massachusetts Institute of Technology, had referred in the 1951 *Stevens' Handbook of Experimental Psychology* to a paper by Gabor regarding sensory processing.

Missing from our Paris dinner conversation was Gabor's development of his "elementary function" which dated to an earlier interest. He had published his paper in the *IEE*, a British journal. I searched for the paper in vain for several years in the American *IEEE* until someone alerted me to the existence of the British journal. The paper was a concise few pages which took me several months to digest. But the effort was most worthwhile:

Before he had invented the Fourier holographic procedure, Gabor had worked on the problem of telephone communication across the transatlantic cable. He wanted to establish the maximum amount a message could be compressed without losing its intelligibility. Whereas telegraphy depends on a simple on-off signal such as the Morse code, in a telephone message that uses language, intelligibility of the signal depends on transmission of the spectra that compose speech. The communicated signals are initiated by vibrations produced by speaking into the small microphones in the phone.

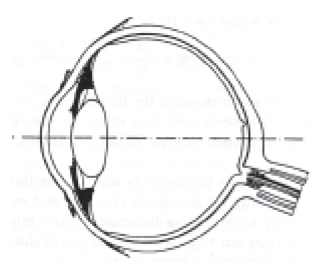
Gabor's mathematical formulation consisted of what we now call a "windowed" Fourier transform, that is, a "snapshot" (mathematically defined as a Hilbert space) of the spectrum created by the Fourier transform which otherwise would extend the spectral analysis to infinity.

Neither the transatlantic cable nor the brain's communication pattern extends to infinity. The Gabor function provides the means to place these communication patterns within coordinates where the spectrum is represented on one axis and space-time on the other. The Fourier transform lets us look at either space-time or spectrum; the Gabor function provides us with the ability to analyze a communication within a context of both space-time and spectrum.

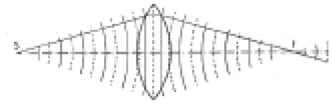
## From Retina to Brain

Licklider, in his 1951 *Handbook of Experimental Psychology* article, suggests that:

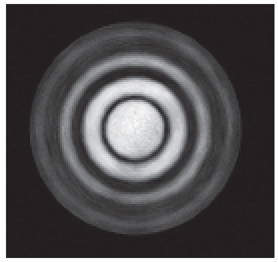
> *If we could find a convenient way of showing not merely the amplitudes of the envelopes but the actual oscillations of the array of resonators, we would have a notation of even greater generality and flexibility, one that would reduce under certain idealized assumptions to the spectrum and under others to the wave form. The analogy to the position-momentum and energy-time problems that led Heisenberg in 1927 to state his uncertainty principle . . . has led Gabor (1946) to suggest that we may find the solution [to the problem of sensory processing] in quantum mechanics.*



*30. Cross section of the eye showing biconcave lens*



*31. Biconvex lens processing wave fronts*



*32. Airy Disc*

Note that Licklider is focusing on the oscillations of resonators (the hair cells of the inner ear) and that he clearly distinguishes spectrum from space-time wave forms as is performed by the Fourier procedure. The analogy to quantum processes is prescient.

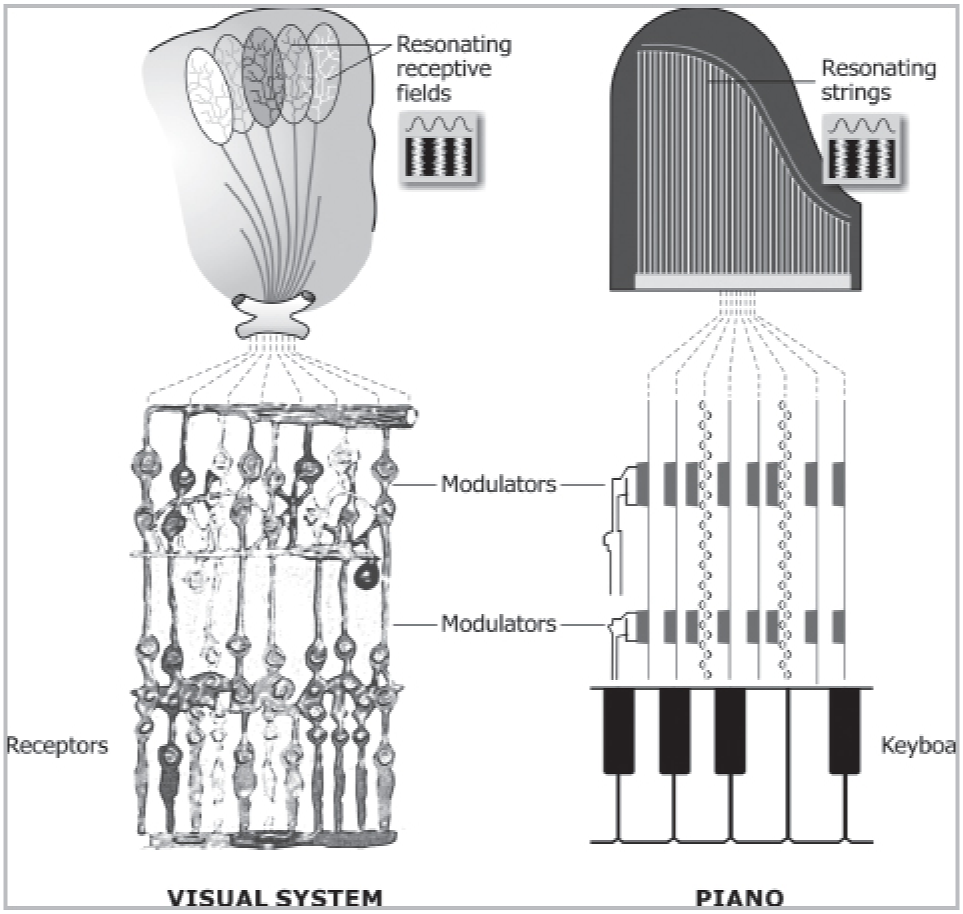
Licklider stated that the problems regarding hearing that he had discussed might find a resolution in Gabor's treatment of communication. That resolution is given, by the Gabor elementary function, a "windowed," constrained, Fourier transformation. For me, the Gabor function provided the missing description to understanding the transformation that is taking place not only in the auditory but also in the visual process between the retina and the brain's cortex.

As has often been noted, revolutions in science require many more steps than are apparent when we are only aware of the final result: We move forward, only to drop back a few paces when we forget what we have discovered. This is true for individuals as well as for the community. I have on several occasions found that I have backed into old ways of thinking that I thought I had abandoned. My rediscovery of Gabor's elementary function, which he himself had momentarily forgotten while we were in Paris, proved to be a great leap forward in how to think about sensory processing in the brain.

The example Gabor used was taken from music: the pitch of a single tone is dependent on the frequency of vibration; the duration of the tone is measured in time. The complete mathematical description of the tone must therefore include both its frequency (and in case of harmonics, the spectrum) and its duration. Gabor's transformation provides simultaneous space-time and frequency coordinates, whereas, when using Fourier's transformation, we must choose between space-time or a spectrum of frequencies. The non-spectral coordinate in the Gabor function includes both space and time because a message not only takes time to be transmitted but also occupies space on the cable.

In brain science, we also use spatial as well as temporal frequency (spectral) coordinates to describe our findings. In addition, when we deal with a spectrum of frequencies per se, we often substitute the term “spectral density” to avoid a common confusion that Gabor pointed out in his paper: non-mathematicians, even physicists, often think of frequencies as occurring only in time, but when mathematicians deal with vibrations as in the Fourier transform, frequencies are described as composing spectra and devoid of space and time.

In Gabor’s pioneering 1946 paper, he found the mathematics for his “windowed” Fourier transform in Werner Heisenberg’s 1925 descriptions of quantum processes in subatomic physics. In reference to Heisenberg’s use of mathematics to describe subatomic quantum processes, Gabor called his elementary unit a “quantum of information.” When, therefore, in the early 1970s, my laboratory as well as brain scientists the world over began to find that the receptive fields of cortical cells in the visual and tactile systems could be described as two-dimensional Gabor functions, we celebrated the insight that windowed Fourier transforms describe not only the auditory but other sensory processes as well.



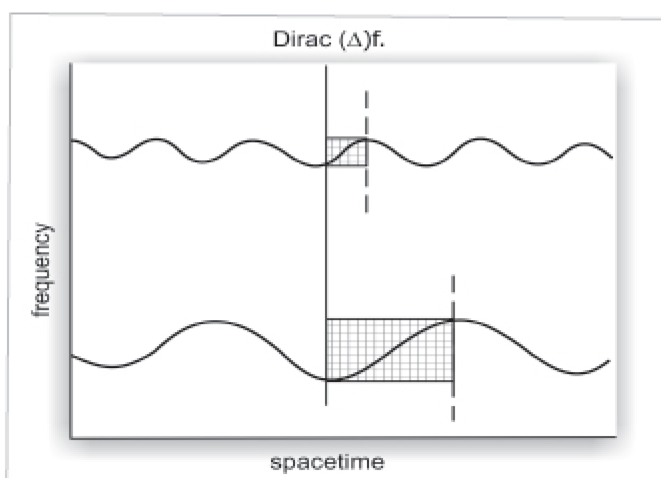

*33. OHM and Helmholtz's Piano Model of Sensory Processing*

The form of communication, a mental process, and the form of the construction of cortical receptive fields, a material physical process, could now be described by the same formalism. At this level of inquiry, an identity is established between the operations of mind and of brain. This identity has led ordinary people, as well as scientists and philosophers, to talk as if their brain "thinks," "chooses," "hurts," or is "disorganized." In the language of philosophy, this is termed misplaced concreteness: It is we the people who do the thinking, choosing, hurting, and who become discombobulated. So it is important to specify the level, the scale of inquiry, at which there is an identity of form (at the receptive field level in the brain) and where mind (communication) and body (brain) are different. More on this in Chapters 22–24.

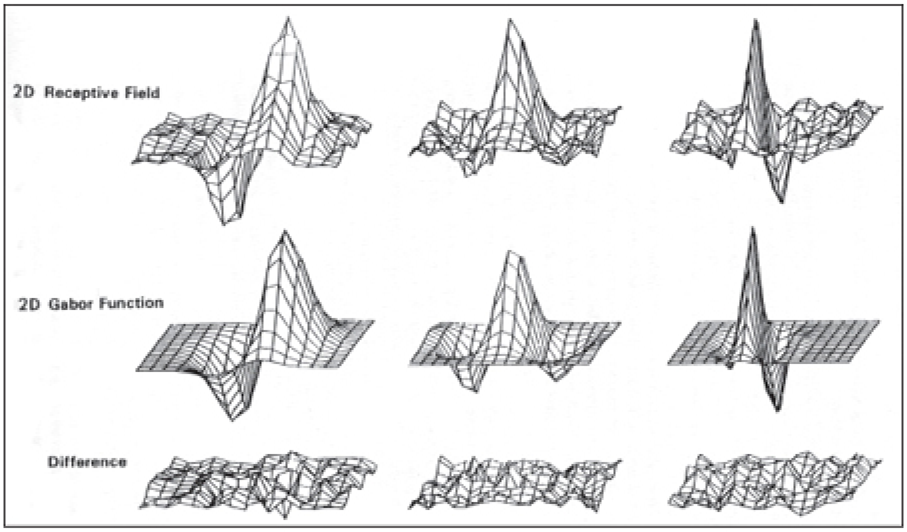
# Implications

Gabor warned against thinking that the "quantum of information" means that communication is actually going on at the quantum scale. I have also cautioned against assuming that the receptive fields we map in the sensory cortex are quantum-scale fields. But when communication is wireless (or uses optical fibers) the medium of communication is operating at the quantum scale. The same may be true for the brain. I noted earlier that the retina is sensitive to individual quanta of radiation. Therefore, for the past decade or more my colleague, Menas Kafatos and I have explored the variety of scales at which brain processes that mediate the organization of receptive fields could actually be quantum-scale and not just quantum-like.

Thus, Mari Jibu and Kunio Yasui, an anesthesiologist and a physicist from Notre Dame Seishen University in Okayama, Japan, and I have suggested that the membranes of the fine fibers, the media in which the receptive fields are mapped, may have quantum-scale properties. The membranes are made up of phospholipids, oscillating molecules that are arranged in parallel, like rows of gently waving poplar trees. The lipid, fatty water- repellent part makes up the middle, the trunks of the "trees," and the phosphorus water-seeking parts make up the inside and outside of the membrane. These characteristics suggest that water molecules become trapped and aligned in the phosphorus part of the membrane. Aligned water molecules can show super-liquidity and are thus super-conductive; that is, they act as if they had quantum-scale properties.




*34. Logons, Gabor Elementary Functions: Quanta of Information*



Visual receptive fields recorded from the cortex and their simulation by Gabor functions.

*35. Top row: illustrations of cat simple 2-D receptive field profiles. Middle row: best-fitting 2-D Gabor wavelet for each neuron. Bottom row: residual error of the fit, which for 97% of the cells studied was indistinguishable from random error in the Chi-squared sense. from: Daugman, J.G. (1990.)*

Another interesting consequence of Gabor's use of the "quantum of information" is the very fact that the form of quantum theory becomes extended to communication. My colleagues in quantum physics at George Mason University in Northern Virginia claim that this means that the laws of quantum physics actually cross all scales from the subatomic to cosmic. My reaction has been: of course, since much of what we know comes to us via our senses and thus through the "lenses" that process spectra such as those named "light" and "heat." But it also means that if quantum laws operate at every scale, then despite their weirdness, these laws should have an explanation at an everyday scale of inquiry. My suggestion is that weirdness originates in the coordinates within which quantum laws are formulated: the creation of a computational region that has spectrum for one axis and space-time for the other. Conceptually, explanations seesaw from spectra (and more often their origins in waveforms) to space-time and particles. We can sort out the weirdness by coming back to the Fourier transform that clearly distinguishes space-time explanations from holographic-spectral explanations.

# Holographic Brainwaves?

At a recent conference I was accosted in a hallway by an attendee who stated that he had great trouble figuring out what the brain waves were that constituted the dendritic processing web. I was taken aback. I had not thought about the problem for decades. I replied without hesitation, “Brain waves! There aren’t any. All we have is oscillations between excitatory and inhibitory post- (and pre-) synaptic potential changes.” I went on to explain about Gabor “wavelets” as descriptive of dendritic fields and so forth.

It’s just like water. When the energy of a volley of nerve impulses reaches the “shore” of the retina the pre-synaptic activation forms a “wave-front.” But when activity at the brain cortex is mapped we obtain wavelets, Gabor’s “quanta of information.” The relationship between the interference patterns of spectra and the frequencies of patterns of waves is straightforward, although I have had problems in explaining the relationship to students in the computational sciences. Waves occur in space-time. Spectra do not. Spectra result from the interference among waves—and, by Fourier’s insightful technique, the locus of interference can be specified as a number that indicates the “height” of the wave at that point. The number is represented by a Gabor function (or other wavelet.) Frequency in space-time has been converted to spectral density in the transform domain.

Wavelets are not instantaneous numbers. As their name implies wavelets have an onset slope and an offset slope. Think of a musical tone: you know a little something about where it comes from and a little as to where it is leading.

Note that we are dealing with dendritic patches limited to one or a small congregation of receptive fields—like the bobbing of a raft in the water beyond the shore. There was a considerable effort made to show that there is no overall Fourier transform that describes the brain’s relationship to a percept—but those of us who initially proposed the holographic brain theory always described the transformation as limited to a single or a small patch of receptive fields. By definition, therefore, the Fourier transformation is constrained, windowed, making the transformed brain event a wavelet.

We now need to apply these formulations to specific topics that have plagued the study of perception— needlessly, I believe. The concept that the optics of the eye create a two-dimensional “retinal image” is such a topic.

## Gabor or Fourier?

*The form of receptive fields is not static. As described in the next chapter, receptive field properties are subject to top-down (cognitive) influences from higher-order brain systems. Electrical stimulation of the inferior temporal cortex changes the form of the receptive fields to enhance Gabor information processing— as it occurs in communication processing systems. By contrast, electrical stimulation of the prefrontal cortex changes the form of the receptive fields to enhance Fourier image processing—as it is used in image processing such as PET Scans and fMRI and in making correlations such as in using FFT. The changes are brought about by altering the width of the inhibitory surround of the receptive fields. Thus both Gabor and Fourier processes are achieved, depending on whether communication and computation or imaging and correlations are being addressed.*

## And Back Again: Projection

We experience the world in which we navigate as being “out there,” not within our sense organs or in our brain. This phenomenon is called “projection.” I experienced an interesting instance of projection that anyone can repeat in his own bathroom. I noted that the enlarging mirror (concave 7X) in my bathroom reflected the ceiling light, not at the mirror’s surface as one would expect, but instead, the image of the light was hovering in mid-air above the mirror. The image seemed so real that I tried to grasp it, to get my hand behind it, only to catch thin air.

Our experience of waveforms, as they create images reflected by mirrors, refracted by prisms or gratings, often seem equally “hard to grasp.” But the power that generates such waveforms can be experienced in a very real way, as in a tsunami sweeping ashore. My research has been motivated by the excitement of “getting behind” the images we experience —to try to understand how the experience is created. Cosmologists spend their days and nights trying to “get behind” the images they observe with their telescopes and other sensing devices. Brain scientists are, for the most part, not yet aware of the problem.

In order to understand the process by which we perceive images, we need to regard vision as akin to other senses, such as hearing. Harvard physiologist and Nobel laureate Georg von Békésy began his classical experiments, summarized in his 1967 book *Sensory Inhibition,* at the Hungarian Institute for Research in Telegraphy in 1927. His initial experiments were made on the basilar membrane of the cochlea, the receptor surface of the ear. Békésy began by examining how the arrival of pressure waves becomes translated into a neural code that reaches our brain. "The results suggested similarities to Mach's law of [visual] brightness contrast. At the time my attempt to introduce psychological processes into an area that was held to be purely mechanical met with great opposition on the part of my associates in the Department of Physics.

. . . And yet I continued to be concerned with the differences between perceptual observations and physical measurements. My respect for psychological observation was further enhanced when I learned that in some situations, as in the detection of weak stimuli, the sense organs often exhibit greater sensitivity than can be demonstrated by any purely physical procedure. (Ernst Mach was a venerated Viennese scientist/philosopher active at the turn of the 20th century.)

When I met Békésy at Harvard, he was frustrated by the small size of the cochlea and was searching for as large a one as he could get hold of. He knew that I was working (in Florida) with porpoises at the time, and he asked me to bring him a porpoise cochlea if I came across one of the animals that had died. I did, but Békésy wanted something still larger.

Békésy had noted at the time—just as we would later come to view the eye as similar to the ear—that the skin was also like the ear in many respects. (The mammalian ear is derived from the lateral line system of fish, a system that is sensitive to vibrations transmitted through water.) Therefore, Békésy set out to make an artificial ear by aligning five vibrators that he could tune to different frequencies. He placed this artificial cochlea on the inside surface of the forearm, and he adjusted the vibrations so that the phase relations among the vibrations were similar to those in a real cochlea. What one felt, instead of the multiple frequencies of the five vibrators, was a single point of stimulation. Békésy showed that this effect was due to "sensory inhibition;" that is, the influence of the vibrators on the skin produced "nearest neighbor" effects, mediated by the network of nerves in the skin, that resulted in a single sensation. Changing the phase relations among the vibrators changed the location on the forearm where one felt the point.

Subsequently, in my laboratory at Stanford, a graduate student and I set to examining whether the brain cortex responded to such individual vibratory stimuli or to a single point as in the sensation produced in Békésy's experiment. We did this by recording from the brain cortex of a cat while the animal's skin was being stimulated by several vibrators. Békésy, who had moved to Hawaii from Harvard (which belatedly offered him a full professorship after he received his Nobel Prize) served on my student's thesis committee; he was delighted with the result of the experiment: The cortical recording had reflected the cat's sensory and cortical processing—presumably responsible for the cat's perceptions—not the physical stimulus that had been applied to the skin on the cat's lips.

On another occasion, still at Harvard, Békésy made two artificial cochleas and placed them on his forearms. I was visiting one afternoon, and Békésy, full of excitement, captured me, strapping the devices on my arms with great enthusiasm. He turned on his vibrators and adjusted the phase relations among the vibrations within each of the "cochleas" so that I experienced a point sensation on each arm. Soon, the point sensations began to alternate from arm to arm: when I felt a point in one arm, I did not feel it in the other. Interesting.

Békésy had concluded from this experiment that sensory inhibition must occur not only in our skin but somewhere in the pathways from our skin to our brain, a conclusion confirmed by the results of our cat experiments.

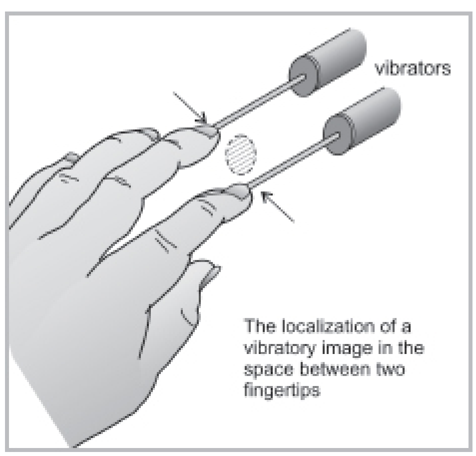
But this was not all. Békésy asked me to sit down and wait a while as the point sensations kept alternating from one arm to the other. I began reading some of his reprints. Then, suddenly, after about ten minutes, I had the weirdest feeling: The sensation of a point had suddenly migrated from my arms and was now at a location in between them, somewhat in front of me. I was fascinated.

I asked, how could this be? How can I feel, have a tactile sensation, outside of my body? Békésy replied with a question: "When you do surgery, where do you feel the tissue you are touching with your forceps and scalpel?" "Of course," I answered, "out there where the tissue is—but the forceps and scalpel provide a solid material connection." We all have this experience every time we write with pen or pencil, feeling the surface of the paper through the mediation of the implement.

But we also hear sounds without any obvious solid material connection with the source that produces them: for instance, the loudspeakers in a stereo system. I once heard the sound so realistically coming out of a fireplace flanked by two stereo-speakers that I actually looked up the chimney to see if there was another speaker hidden up there.

There are important advantages to our ability to project our perceptions away from our bodies in this fashion. In another experiment in which he set out to test the value of our stereo capability, Békésy plugged his ears and used only one loudspeaker, strapped to his chest, to pick up sounds in his environment. He tried to cross a street and found it almost impossible because he could not experience an approaching car until it was almost literally upon him. The impact of the vibrations on his chest from the approaching sound of a car hit him so suddenly that he clutched his chest and was nearly bowled over.

We may experience the world we navigate as being "out there," but the apparatus that makes our experience possible is within our skin. My eyes and brain enable me to see—but the location of what I see is projected out, away from and beyond those bodily structures that make my seeing possible. Békésy's experiments demonstrated the laws of projection create an anticipatory frame, a protective shell that surrounds us and allows us to choose an action before an oncoming event overwhelms us.




*36. Localization of Perception Between Fingers*

While reading Békésy's notes on his experiments, I saw that he had scribbled some equations next to the text.

I asked him about them, and he answered that they were some new-fangled math that he did not fully understand as yet. I felt that, even if he understood the equations, I certainly would not. To my surprise, that understanding was to come later: they were the equations describing Gabor's application to sensory processing of the mathematics of quantum physics.

My encounters with Békésy were among the most rewarding in my career: they greatly enhanced my appreciation of the issues to be faced in deciphering how we navigate our world.

The experimental results presented here showed that the perceptual process is far from a simple input of "what's out there" to the brain. Rather, by means of the transformations produced by receptors, structures such as objects are formed from a holographic-like background within which every-"thing" is distributed "everywhere and everywhen." The receptor then transforms these "objects"—in the case of vision by virtue of the quantum nature of retinal processing—into a constrained holographic-like process, a set of wavelets that Dennis Gabor called "quanta of information." Békésy's experiments, as well as my own, demonstrated that, in turn, these brain processes influence receptors as much as does the input from the-world-out-there that we navigate. More on this in the next chapter.

## In Summary

In this chapter I summarize the hard evidence for why we should pay attention to the transformations that our receptors and sensory channels make—rather than thinking of these channels as simple throughputs. This evidence provides a story far richer than the view of the formation of perception held by so many scientists and philosophers.

Furthermore, when we separate the transformations produced by our lenses and lens-like processes from those produced by our retinal processing, we can demonstrate that the brain processing of visual perception is actually multidimensional. For other senses I presented the evidence that "sensory inhibition" serves a similar function. Thus there is no need for us to deal with the commonly held view that brain processes need to supplement a two-dimensional sensory input.

*Finally, I place an emphasis on the data that show that perception has the attribute of “projection” away from the immediate locus of the stimulation. We often perceive objects and figures as “out there,” not at the surface of the receptor stimulation.*

*A corollary of projection is introjection. I thus now venture to suggest that introjection of perceptions makes up a good deal of what we call our ”conscious experience.”*

# Chapter 6
## Of Objects and Images

Wherein I distinguish between objects and images and the brain systems that process the distinction.

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*Thus, by our movements we find it is the stationary form of the table in space, which is the cause of the changing image in our eyes. We explain the table as having existence independent of our observation because at any moment we like, simply by assuming the proper position with respect to it, we can observe it.*

—Hermann von Helmholtz, *Optics,* 1909/1924

*As Lie wrote to Poincaré in a letter in 1882: 'Riemann and v. Helmholtz proceeded a step further [than Euclid] and assumed that space is a manifold or collection of numbers. This standpoint is very interesting; however, it is not to be considered definitive.' Thus, Lie developed the means to analyze rigorously how points in space are transformed into one another through infinitesimal transformations—that is, continuous groups of transformations.*

—Arthur I. Miller, *Imagery in Scientific Thought,* 1984

## Movements

The end of the previous chapters left feature creatures with stick figures and frequency freaks with a potential of wavelets. Stick figures are two-dimensional, but the world we navigate is four-dimensional. Nor is that world composed of wavelets; it is filled with objects. Nor is that world composed of wavelets filled with objects. Early on I had the intuition that somehow movement might be the key to unveiling the process by which we are able to perceive objects in a four-dimensional world. My intuition was based on the observation that adjacent to—and sometimes overlapping with—those areas of the brain that receive a sensory input to the brain, there are areas that, when electrically stimulated, produce movements such as turning the head and eyes, perking the ears, and moving the head and limbs. Such movements are mediated by our brain's circuitry, its surface structure.

But how would our perception of objects be achieved through movement? While teaching at Georgetown, two of my undergraduate students were to provide the route by which I came to a first step toward answering this question. One student kept insisting that he wanted to know "the how, the particular go of it." Another student in a different class had a condition called "congenital nystagmus." Nystagmus is the normal oscillation of our eyeballs. In people such as my student, the oscillation is of much greater amplitude and is therefore quite noticeable. I had had several patients with this harmless "symptom," and I told my student that she had nothing to worry about. This turned out to be a bigger worry to her: she no longer had an "ailment" that made her special. During class, while I was lecturing on another topic, from time to time I also looked at this student's big brown oscillating eyes. I began to have the feeling that those eyes were trying to tell me something. Shortly, while still lecturing, the first part of the answer came: I recalled that the ability to perceive at all depends on oscillatory *movements*.

Experiments have shown us that when the oscillation of the eyes is nullified, vision disappears within 30 seconds. In the experiments, a small mirror was pasted on the test subject's sclera, the white part of the eyeball. This is not as uncomfortable as it might seem. The sclera is totally insensitive to touch or pain; it is when the cornea, the colored ring around the pupil of our eye, is injured, that it hurts so much. A figure is then projected onto the mirror and reflected from that mirror onto a surface displayed in front of the subject. Thus, (when corrected for the double length of the light path to and from the eye) the figure displayed on the surface in front of the subject mirrors the excursion of the eyeball. Shortly, the subject experiences a fading of the figure, which then disappears within about 30 seconds. Hence, as this experiment clearly demonstrates: no oscillatory movement, no image.

These same results have been repeatedly obtained in experiments involving other senses. Fine oscillations of our receptors or of the stimulating environment around us are needed in order for us to see, to feel by touch, and to hear. These oscillations—vibrations measured in terms of their frequencies—allow us to experience images in the space-time that surrounds us.

The nystagmoid oscillations of the eyes act like a pendulum. The arc that a pendulum describes moves back and forth across a point where the pendulum comes to rest when it stops swinging. Current mathematical descriptions call such a point an "attractor." (Mathematically, the ideal point attractor is defined as an essential character of a system of group-theoretical oscillations that in time converge on it.) Thus the oscillations of the eyes form a point attractor in the neuro-nodal deep structure of fine fibers that can then serve as a pixel. Pixels are the units from which the images on your television screen are formed.

*Forming a point attractor, a pixel, from oscillations is a transformation. The transformation converts the frequency of oscillations in the spectral domain to points in space-time. In short, the transformation is described by the (inverse) Fourier equation.* It is the oscillatory *movements*, because of their pendulum-like character, that transform a distributed holographic-like brain process to one that enables imaging. Converting from space-time to frequencies and back to space-time is the procedure that is used to produce images by PET scans and fMRIs in hospitals.

## What's the Difference?

Our experience of the world is initially with objects, not images. The distinction between objects and images is fundamental to our understanding of how we perceive the world around us. We can look at objects from various perspectives to perceive various profiles, images, of the objects, but the imaging is secondary to the perception of objects. To perceive objects, either they or we make large-scale movements. Helmholtz made this distinction well over a century ago: he stated that objects are forms that remain unchanged *despite* movement; images are those perceptions that change *with* movement.

To demonstrate the distinction between objects and images, I conduct a simple demonstration. I have a volunteer, a student or a person attending a conference, close her eyes and extend her hand palm up. I then tap her palm with a key. I ask what she experiences. Ordinarily, the answer is "a poking on my palm." Next I put the key into her palm, ask her to close her hand, moving her fingers. Again I ask what she is experiencing. Invariably, the answer is "a key." Poking is imaged as happening "to me"; when the volunteer is moving her hand and fingers, she experiences an *object* "out there."

In the auditory mode, the distinction between image and object is the basis of the difference between music and speech. We hear music; we speak speech. Music is centered on the ear; language is centered on the tongue (*lingua* in Latin). For instance, tones are images, profiles, which change as changes take place in the context within which they occur. Such tones, including vowel sounds, can be described as Gabor functions that embody what has come before and anticipate what is yet to come. By contrast, our perception of consonants is that they are like objects in that they remain stable over a wide range of changing contexts. Simulations that have been designed with the intent to produce gradual transitions between consonants such as "b" and "p" or "d" and "t" show that we do not perceive such gradations in sound. Technically, this phenomenon is known as "categorical perception."

As higher-order constructions are composed, both music and language contain images and objects. Still, the distinction between being touched by music and actively forming speech is upheld because, at least in untrained subjects, musical images, tunes, tend to be processed primarily with the right hemisphere of the brain while ordinary language is more likely to be processed by the left hemisphere.

Another example of the distinction between our perception of images and of objects is provided by the sun's radiant energy that warms and feeds us. When that radiant energy affects us, we "name" it light or heat, but it is not such when it occurs in outer space. It takes a considerable amount of active instrumentation by telescopes and interferometers to demonstrate that *radiation exists as such*. Physicists often use terms like "heat" or "light" to describe radiations of different wavelengths—a shortcut that can lead to confusion, not only for nonscientists, but, as well, even for the physicists who have used these labels. By contrast, in psychophysics we use the term "luminance" to describe radiation that is physically measured and therefore objective. We use the term "brightness" to describe and measure what we perceive. Radiant energy must fall on a receptor to be perceived as light or heat just as the oscillations of water that mediate its energy must strike the shore to become the breakers with the strength to topple us. In both cases— water and radiation—the patterns that make up the perceived objects—breakers and light/heat—are considerably different from the oscillating energies offshore or out in space.

## An Act of Faith

We are able to perceive objects as the result of relative movement of ourselves within the world we navigate. Thus, objects can be regarded as constructions by our brain systems that are computing the results of those movements.

When I use the term "construction," I do not mean that what we navigate is not a real world. When I hit my shin on the bed rail, I don't doubt, no matter how sleepy I may be, that the navigable world of bed rails is real. This lack of doubt forms a belief that is based on our early experience.

I first understood how a belief is involved in our perception of an objective world while at a conference held at Esalen, the famous West Coast spa and retreat. The situation was somewhat bizarre, as the theme of the conference was brain anatomy. During the conference, we were introduced to some of the New Age exercises. One of these involved all of us stodgy scientists being blindfolded and going around the campus feeling bushes, flowers, and one another's faces. It was a totally different experience from our usual visual explorations and resulted in my becoming aware of the distinctiveness of perceptions derived from different sensory experiences.

It immediately occurred to me that as babies, we experience our mothers and others around us in different ways with each of our various sensory systems. Each of these experiences is totally different. As we quickly learned at Esalen, our visual experience of a person is very different from our auditory experience of that person, and different still from our experience of touch or of taste! Somewhere along the line, as we process these various inputs, we make a leap of faith: all these experiences are still experiences of the same "someone." In the scientific language of psychology, this is called the process of "consensual validation," validation among the senses.

As we grow older, we extend this faith in the unity of our experiences beyond what our various sensory explorations tell us, and we include what others tell us. We believe that our experiences, when supported by those of others, point to a "reality." But this is a faith that is based on disparate experiences.

The English philosopher Bishop George Berkeley became famous for raising questions regarding this faith. He suggested that perhaps God is fooling us by making all of our experience seem to cohere, that we are incapable of "knowing" reality. Occasionally other philosophers have shared Berkeley's view, which is referred to in philosophy as "solipsism." I suggest that, distinct from the rest of us, such philosophers simply didn't make that consensual act of faith when they were babies.

An extreme form of consensuality is a psychological phenomenon called "synesthesia." Most of us share such experiences in milder form: red is a hot color, blue is cool. Some thrilling auditory and/or visual experiences actually make us shiver. Those who experience synesthesia have many more such sensations—salty is cool; peppery is hot— to a much greater degree.

The usual interpretation is that *connections* between separate systems are occurring in their brains, "binding" the two sensations into one—connections that the rest of us don't make. Instead, it is as likely that synesthesia is due to a *higher-order abstraction*, similar to the process previously described where I asked those students to raise their hands if they wear glasses and also blue jeans. Eyeglasses and blue jeans are conjoined in their response. In my laboratory at Stanford, we found that many receptive fields in the primary visual cortex respond not only to visual stimuli but also to limited bandwidths of auditory stimulation. Still other *conjunctions* within a monkey's receptive field encoded whether the monkey had received a reward or had made an error. Other investigators have found similar cross-modal conjunctions, especially in motor cortexes of the brain. A top-down process that emphasizes such cross-modal properties could account for synesthesia such as the experience of bright sounds without recourse to connecting, “binding” together such properties as hearing and seeing from two separate brain locations.

Our faith arising from consensual agreement works well with regard to our physical environment. Once, when I was in Santiago, Chile, my colleague, the University of California philosopher John Searle rebutted the challenge of a solipsist with the statement that he was happy that the pilot of the plane that brought him through the Andes was not of that persuasion. The pilot might have tried to take a shortcut and fly right into a mountain since it “really” didn’t exist.

When it comes to our social environment, consensuality breaks down more often than not. Ask any therapist treating both wife and husband: one would never believe these two inhabited the same world. The film *Rashomon* portrays non-consensuality beautifully. In later chapters, I will examine some possibilities as to how this difference between social and physical perceptions comes about.

I am left with an act of faith that states that there is a real world and that our brain is fitted to deal with it to some extent. We would not be able to navigate that real world if this were not so. But at the same time, well fitted as our brains are, our experience is still a *construction* of that reality and can therefore become *misfitted* by the operation of that brain. It is the job of brain/behavioral science to lay bare when and how our experience becomes fitting.

In the section on communication we will look at what has been accomplished so far. From my standpoint of a half-century of research, both brain and behavioral scientists have indeed accomplished a great deal. This accomplishment has depended on understanding how the brain makes it possible for us to more or less skillfully navigate the world we live in. This in turn requires us to understand brain functions in relation to other branches of science. Thus, a multiple front of investigators has developed under the heading of “cognitive neuroscience.” This heading that does not do justice to the breadth of interest, expertise and research that is being pursued. For perception, the topic of the current section of this book, the link had to be made primarily with physics. In this arena, theory based on mathematics has been most useful.

## An Encounter

Some years ago, during an extended period of discussion and lecturing at the University of Alberta, I was rather suddenly catapulted into a debate with the eminent Oxford philosopher Gilbert Ryle. I had just returned to Alberta from a week in my laboratory at Stanford to be greeted by my Canadian hosts with: "You are just in time; Gilbert Ryle is scheduled to give a talk tomorrow afternoon. Would you join him in discussing 'The Prospects for Psychology as an Experimental Science'?" I was terrified by this "honor," but I couldn't pass up the opportunity. I had read Ryle's publications and knew his memorable phrase describing "mind" as "the ghost in the machine." I thought, therefore, that during our talk we would be safely enveloped in a behaviorist cocoon within which Ryle and I could discuss how to address issues regarding verbal reports of introspection. But I was in for a surprise.

Ryle claimed that there could not be any such thing as an experimental science of psychology—that, in psychology, we had to restrict ourselves to narrative descriptions of our observations and feelings. He used the example of crossing a busy thoroughfare filled with automobiles, while holding a bicycle. He detailed every step: how stepping off a curb had felt in his legs, how moving the bicycle across cobblestones had felt in his hands, how awareness of on-coming traffic had constrained his course, and so forth. His point was that a naturalist approach, using introspection, was essential if we were to learn about our psychological processes. I agreed, but added that we needed to supplement the naturalist procedure with experimental analyses in order to understand "how" our introspections were formed. Though I countered with solid *results* of many experiments I had done on visual perception, I was no match for an Oxford don. Oxonians are famed for their skill in debating. Ryle felt that my experimental results were too far removed from experience. I had to agree that in experimentation we lose some of the richness of tales of immediate events.

About ten minutes before our time was up, in desperation, I decided to do just what Ryle was doing: *I described my experimental procedure rather than its results*. I compared the laboratory and its apparatus to the roadway's curbs and pavements; I enumerated the experimental hazards that we had to overcome and compared them with the cars on the road; and I compared the electrodes we were using to Ryle's bicycle. Ryle graciously agreed: he stated that he had never thought of experiments in this fashion. I noted that neither had I, and thanked him for having illuminated the issue, adding that I had learned a great deal about the antecedents —the context within which experiments were performed. The audience rose and cheered.

This encounter with Gilbert Ryle would prove to be an important step in my becoming aware of the phenomenological roots of scientific observation and experiment. Ryle's "ghost" took on a new meaning for me; it is not to be excised, as in the extremes of the behaviorist tradition; it is to be dealt with. I would henceforth claim that: *We go forth to encounter the ghost in the machine and find that "the ghost is us."*

## Object Constancy

As noted at the beginning of this chapter, immediately adjacent to— or in some systems even overlapping— the primary sensory receiving areas of the brain, are brain areas that produce movement of the sensing elements when electrically excited. Adjacent to and to some extent overlapping this movement-producing cortex are areas that are involved in making possible consistent perceptions despite movement. My colleagues and I, as well as other investigators, have shown these areas to be involved in perceiving the size and color as well as the form of objects as consistent (called "size, color and object constancy" in experimental psychology.)

In our experiments we trained monkeys to respond to the smaller of two objects irrespective of how far they were placed along an alley. The sides of the alley were painted with horizontal stripes to accentuate its perceived distance. The monkeys had to pull in the smaller of the objects in order to be able to open a box containing a peanut. After the monkeys achieved 90% plus, I removed the cortex surrounding the primary visual receiving area (which included the visuomotor area). The performance of the monkeys who had the cortical removals fell to chance and never improved over the next 1000 trials. They always "saw" the distant object as smaller. They could not correct for size constancy on the basis of the distance cues present in the alley.

## The Form(ing) of Objects

Our large-scale movements allow us to experience objects. Groundbreaking research has been done by Gunnar Johanssen in Uppsala, Sweden, and James Gibson at Cornell University in Ithaca, New York. Their research has shown how objects can be formulated by moving points, such as the pixels that we earlier noted were produced by nystagmoid oscillations of the eyes. When such points move randomly with respect to each other, we experience just that— points moving at random. However, if we now group some of those points and consistently move the group of points as a unit within the background of moving points — Voilà! We experience an object. A film made by Johanssen and his students in the 1970s demonstrates this beautifully. The resulting experience is multidimensional and sufficiently discernible that, with a group of only a dozen points describing each, the viewer can tell boy from girl in a complex folk dance.

Though some of the film is made from photographs of real objects, computer programs generated most of it. I asked Johanssen whether he used the Fourier transform to create these pictures. He did not know but said we could ask his programmer. As we wandered down the hall, he introduced me to one Jansen and two other Johanssens before we found the Johanssen who had created the films. I asked my question. The programmer was pleased: "Of course, that's how we created the film!"

But the Johanssen film shows something else. When a group of points, as on the rim of a wheel, is shown to move together around a point, the axel, our perception of the moving points on the rim changes from a wave form to an object: the "wheel." In my laboratory we found, rather surprisingly, that we could replace the "axel" by a "frame" to achieve the same effect: a "wheel." In experimental psychology this frame effect has been studied extensively and found to be reciprocally induced by the pattern that is being framed.

This experimental result shows that movement per se does not give form to objects. Rather, the movements must cohere, must become related to one another in a very specific manner. Rudolfo R. Llinás provided me with the mathematical expressions of this coherence in personal discussions and in his 2001 book, *I of the Vortex: From Neurons to Self*. My application of his expressions to our findings is that the Gabor functions that describe sensory input cohere by way of covariation; that the initial coherence produced by movements among groups of points is produced by way of contravariation (an elliptical form of covariation); and that the final step in producing object constancy is the “symmetry group” invariance produced by a merging of contravariation with covariation.

# Symmetry Groups

Groups can be described mathematically in terms of symmetry. A Norwegian mathematician, Sophus Lie, invented the group theory that pertains to perception. The story of how this invention fared is another instance of slow and halting progress in gaining the acceptance of scientific insights. As described in the quotation at the beginning of this chapter, early in the 1880s Hermann von Helmholtz, famous for his scientific work in the physiology of vision and hearing, wrote to Henri Poincaré, one of the outstanding mathematicians of the day. The question Helmholtz posed was ”How can I represent objects mathematically?” Poincaré replied, “Objects are relations, and these relations can be mapped as groups.” Helmholtz followed Poincaré’s advice and published a paper in which he used group theory to describe his understanding of object perception. Shortly after the publication of this paper, Lie wrote a letter to Poincaré stating that the kind of discrete group that Helmholtz had used would not work in describing the perception of objects—that he, Lie, had invented continuous group theory for just this purpose. Since then, Lie groups have become a staple in the fields of engineering, physics and chemistry and are used in everything from describing energy levels to explaining spectra. But only recently have a few of us returned to applying Lie’s group theory to the purpose for which he created it: to study perception.

My grasp of the power of Lie’s mathematics for object perception was initiated at a UNESCO conference in Paris during the early 1970s. William Hoffman delivered a talk on Lie groups, and I gave another on microelectrode recordings in the visual system. We attended each other’s sessions, and we found considerable overlap in our two presentations. Hoffman and I got together for lunch and began a long and rewarding interaction.

Symmetry groups have important properties that are shown by objects. *These groups are patterns that remain constant over two axes of transformation*. The first axis assures that the group, the object, does not change as it moves across space-time. The second axis centers on a fixed point or stable frame, and assures that changes in size—radial expansion and contraction—do not distort the pattern.

## What We Believe We Know

To summarize: *We navigate a world populated by objects. Objects maintain their form despite movements. What vary are images—that is, profiles of objects that change with movement. But even our perceptions of images depend on motion*.

Minute oscillations of the relation between receptor and stimulus are necessary for *any* perceptual experience to occur. These oscillations describe paths around stable points—called "point attractors." Point attractors are the result of transformations *from* the oscillations that describe the sensory input in the spectral domain, *to* space-time "pixels" from which images are composed.

When points become grouped by moving together with respect to other points, the group is perceived as a form—that is, an object. The properties of objects, the invariance of their perceived form over changes in their location and apparent size are described by a particular kind of group called a "symmetry group."

A more encompassing picture of how we navigate our world can be obtained by considering a corollary of what I have described so far. Recall that, in introducing his suggestion to Helmholtz that he use groups, Poincaré noted that "objects are relations." Thus, Poincaré's groups describe relations among points, among pixels within a frame, *a context* that occurs in space and time.

Such contexts are bounded by horizons, the topic of the next chapter.

# Chapter 7
## The Spaces We Navigate and Their Horizons

Wherein I distinguish a variety of spaces we navigate and discern the boundaries at several of their horizons.

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> *When it was time for the little overloaded boat to start back to the mainland, a wind came up and nudged it onto a large rock that was just below the surface of the water. We began, quite gently, to sink. . . . All together we went slowly deeper into the water. The boatman managed to put us ashore on a huge pile of rocks. . . .*
>
> *The next day when I passed the island on a bus to Diyarbakir there, tied to the rock as we had left it, was a very small, very waterlogged toy boat in the distance, all alone.*
>
> —Mary Lee Settle, *Turkish Reflections: A Biography of a Place,* 1991

## Navigating the Spaces We Perceive

Have you considered just how you navigate the spaces of your world? Fortunately, in our everyday living, we don't have to; our brain is fine-tuned to do the job for us. Only when we encounter something exceptional do we need to pay attention. When we are climbing stairs, we see the stairs with our eyes. The space seen is called "occulocentric" because it centers on our eyeballs, but it is our body that is actually climbing the stairs. This body- centered space is called "egocentric." The stairs inhabit their own space: some steps may be higher than others; some are wider, some may be curved. Stairs are objects, and each has its own "object-centered" space. Space, as we navigate it, is perceived as three-dimensional. Since we are moving within it, we must include time as a fourth dimension. We run up the stairs, navigating these occulocentric, egocentric, and object-centered spaces without hesitation. The brain must be simultaneously computing within 12 separate co-ordinates, four dimensions for each time-space. Cosmologists are puzzling the multidimensionality of "string" and "brane" theory: why aren't scientists heeding the 12 navigational coordinates of brain theory?

Now imagine that the stairs are moving. You are in a hurry, so you climb these escalator stairs. You turn the corner and start climbing the next flight of stairs. Something is strange. The stairs seem to be moving but they are not, they are stationary. You stumble, stop, grab the railing, then you proceed cautiously. Your occulocentric (visual) cues still indicate that you are moving, but your egocentric (body) cues definitely shout "no." The brain's computations have been disturbed: occulocentric and egocentric cues are no longer meshed into a smoothly operating navigational space. It is this kind of separation—technically called "dissociation"— that alerts us to the possibility that the three types of space may be constructed by different systems of the brain.

## Eye-Centered and Body-Centered Systems

While in practice in Jacksonville, Florida, I once saw a patient who showed an especially interesting dissociation after he'd been in an automobile accident. Every so often, he would experience a brief dizzy spell, and when it was over, he experienced the world as being upside down. This experience could last anywhere from a few minutes to several hours, when it was ended by another dizzy spell, after which his world turned right side up once more. This patient was an insurance case, and I had been asked by the insurance company to establish whether he was faking these episodes. Two factors convinced me that he was actually experiencing what he described: his episodes were becoming less frequent and of shorter duration; and his main complaint was that when the world was upside down, women's skirts stayed up around their legs, despite gravity!

In the short time of this office visit I had failed to ask the patient what proved to be a critical question: Where were your feet when the world was upside down? Decades later I had the opportunity to find the answer to this question.

The story begins more than a hundred years ago when George Stratton, an early experimental psychologist, performed an experiment at Stanford University. He had outfitted himself with spectacles that turned the world upside down, just as the world had appeared to my patient. However, after continuously wearing these glasses for a week during his everyday activities, Stratton found that his world had turned right side up again.

Poincaré had stated that objects are relations; therefore, the perceived occulocentric space, which is made up of objects, is relational, something like a field whose polarity can change: Thus, "up" versus "down" is, in fact, a relationship that adjusts to the navigational needs of the individual. With respect to my question as to where one's feet are located in such an upside-down/down-side-up world, why not repeat Stratton's experiment and ask whether occulocentric and egocentric spaces become dissociated? My opportunity arose when two of my undergraduate students at Radford University in Virginia volunteered to repeat the experiment. One would wear the prism-glasses; the other would guide him around until his world was again negotiable, right side up.

Once the perceptions of the student wearing the glasses had stabilized, I had my chance to ask the long-held question: Where are your feet? "Down there," my student said and pointed to his shoes on the ground. I placed my hand next to his and pointed down, as he had, and he saw my hand as pointing down.

Then I stepped away from him and placed my hand in the same fashion, pointing to the ground as I saw it. He, by contrast, saw my hand as pointing up! As I brought my hand closer to his body, there was a distance at which he became confused about which way my hand was pointing, until, when still closer to his body, my hand was perceived as pointing in the same direction as he had originally perceived it when my hand was next to his.

The region of confusion was approximately at the distance of his reach and slightly beyond.

Occulocentric and egocentric spaces are therefore dissociable, and each of these is also dissociable from object-centered spaces. After brain trauma, patients have experienced "micropsia," a condition in which all objects appear to be miniscule, or "macropsia" where objects appear to be oversized. In these conditions, occulocentric and egocentric spaces remain normal.

Conceived as fields, it is not surprising that the objects in these spaces are subject to a variety of contextual influences. Some of these influences have been thoroughly investigated, such as the importance of frames in object perception; others, such as those in the Stratton experiment have been thoroughly studied, but no explanation has been given as to how such a process can occur, nor has an explanation been given for micropsia and macropsia.

I will venture a step toward explanation in noting that the Fourier theorem and symmetry group theory offer, at the least, a formal scaffolding for an explanation. The brain process that transforms the sensory input from the space-time domain optical image to the spectral domain at the primary visual cortex, and back to the space-time domain by way of movement, actually should end up with up-down *mirror* images of the occulocentric space. This is mathematically expressed in terms of "real" and "imaginary" numbers—that is, as a real and a virtual image. Ordinarily we suppress one of these images—probably by movement, but exactly how has not been studied as yet.

We noted in the previous chapter that symmetry groups have the characteristic that the group, the object, remains invariant across expansion and contraction. This means that we ordinarily adjust for what, in a camera, is the zoom of the lens. In my laboratory, my colleagues and I were able to change the equivalent of the zoom of receptive fields in the visual cortex by electrical stimulation of other parts of the cortex and of the basal ganglia of the brain. Patients experienced such a change in zoom during surgery at the University of California at San Francisco when their brains were electrically stimulated in the frontal and in the parieto-temporal regions of their cortex. Perhaps the adjustment of the zoom, which in our experiments was effected through lateral inhibition, becomes disturbed in patients who experience micropsia or macropsia.

Occulocentric space has been studied more thoroughly than the "spaces" of other senses, primarily because painters have been interested in portraying it. Painters needed to portray a three-dimensional perspective on a two-dimensional surface and to take into account the variety of constancies we perceive for objects, depending on the distance they are from us. This brings us to the topic of horizons, a topic that shows how our perceptions depend not only on the brain systems that are involved but also on how these systems become *tuned* by the culture in which we have been raised.

## Nature and Nurture

At the dedication ceremonies of Brandeis University, Abraham Maslow, Wolfgang Köhler and I were discussing perception. Köhler insisted that the way we perceive is inborn. "If learning is involved, it isn't perception," he declared. With regard to perception, Köhler was what is referred to in psychology as a "nativist." Today, it is hard to remember how entrenched this view was; so much evidence has since been obtained that indicates just how what we learn influences how we perceive. Much of this shift in viewpoint is due to the research and writings of Donald Hebb that drew attention to how dependent our current perception of perception is based upon what we have learned.

Hebb's contribution came exactly at the right moment. During the mid-1950s, sitting at my dining room table, Jerome Bruner wrote a landmark paper entitled "The New Look in Perception." Among other experiments, in this paper, Bruner recounted the demonstration that how large we perceive a particular coin to be—a quarter, for instance—depends on how wealthy or poor we are. Such an everyday experience attests to how much the *context* of our perception—in this case, what we have learned about the value of a coin—influences *how* we perceive it.

These insights were anticipated in anthropology and sociology, where studies of peoples of different cultures showed marked differences in their perceptions. For instance, in Somalia there is no appreciation for the color red but a great differentiation of the spectrum that we ordinarily classify as green. The brain processes reflecting such differences are now accessible to study with fMRIs and other brain-imaging techniques.

The argument can still be made that sensitivity to context is inherited. This is largely correct. In fact, the whole discourse on what is inherited and what is learned takes on a new significance when inheritance is considered as a *potential* rather than a full-blown established capacity received at birth. The Nobel laureate, behavioral zoologist Konrad Lorenz made this point with respect to learning: he pointed out that different species have different potentials for learning this or that skill.

Sandra Scarr, professor of psychology at the University of Virginia, has gone a step further in suggesting a test for determining "how much" of a skill is inherited: she has shown that, to the extent to which a perception or skill comes easily—that is naturally—to us, it is, to that extent, inherited. Thus, our ability to speak is highly inborn, but our ability to read is markedly less so. Though we all talk, whether we learn to speak English or Chinese depends on the culture in which we grow up. How fluent we may eventually become in Chinese or in English also depends on learning, which in turn depends on the stage of maturation of our brain when the learning is undertaken.

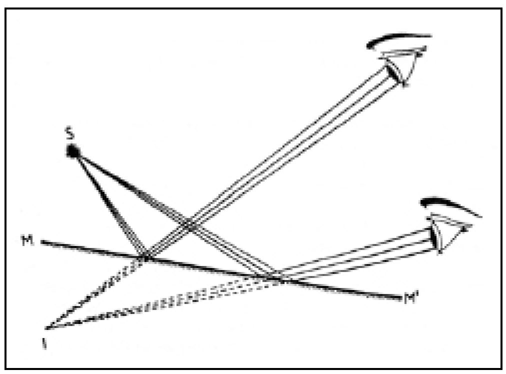
## Mirrors

How we perceive becomes especially interesting, almost weird, when we observe ourselves and the world we navigate in mirrors. Like author and mathematician Lewis Carroll in the experiments he often demonstrated to children, I have all my life been puzzled by mirrors. How is it that within the world of mirrors right and left is reversed for us but up and down is not? How is it that when I observe myself in a mirror, my mirror image is "in the mirror," but the scene behind me is mirrored "behind the mirror?"

Johannes Kepler proferred an answer to these questions in 1604. Kepler noted that a point on the surface of a scene reflects light that becomes spread over the surface of the mirror in such a way that when viewed by the eye, it forms a cone behind the mirror symmetrical to the point. His diagram illustrates this early insight.

I realized the power of the virtual image while reading about Kepler's contribution, lying on a bed in a hotel room. The wall at the side of the bed was covered by a mirror—and "behind" it was another whole bedroom! An even more potent and totally confusing experience occurred while I was visiting a famous "hall of mirrors" in Lucerne, Switzerland. Speak of virtual horizons! I saw my colleagues and myself repeated so many times at so many different distances and in so many different directions that I would certainly have become lost in the labyrinth of images had I not held onto an arm of one of my companions.

On this occasion, I was given a reasonable "explanation" of the how of mirror images. I was told that there had been an explanation presented in *Scientific American* some time ago which was summarized thus: ordinarily we have learned to look forward from back to front—so when we are looking in a mirror we see what is in front of us, behind the mirror, as if we are coming at the virtual image from behind it.




*37. Kepler's diagram of the reflection of a point (S) on a plane mirror (M—M') as seen (I) as a virtual image by a person's eyes*

Support for this explanation comes from an experience many of us have had when we have tried to teach someone else how to tie a necktie (especially a bow tie). If you face the person and try to tie the tie, the task is awkward if not impossible. But if you stand behind the person, look forward into a mirror, and tie his tie, the job is easy.

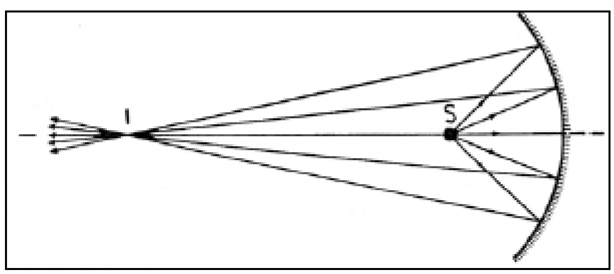
The above observations were made on a plane mirror. A concave mirror presents another wonderful phenomenon. I have a 7X concave mirror in my bathroom. Looking at close distance to my face, I see its reflection "in the mirror." But one day I noted that the bathroom's ceiling light was floating in midair, suspended over the bathroom sink.

Investigating the source of the image showed that when I covered the mirror with my hand the image disappeared.

The examples presented to us by mirrors show that *what* we see depends on *how* we see. The next sections describe some of what we now know about the "how" of seeing.

## Objects in the World We Navigate

How we perceive objects is dependent on brain systems that process invariance, that is, the property of a perception to be maintained despite relative movement between the perceived object and the perceiver. An example is size constancy. In my Stanford laboratory, during the 1970s, my colleagues and I performed the following experiment with monkeys: They were taught to pull a string that was attached to a box containing a peanut. There were two such boxes, one large and one small. The boxes rolled along a rail within an alley whose sides were painted with broad horizontal stripes that enhanced the feeling of distance. Each box could be decoupled from its string so that its placement could readily be exchanged. The monkeys were trained to pull in the box that appeared to them to be the larger. They pulled in the larger box when it was close by *and also when it was way up the alley*. "Larger" was larger to them at both distances.




*38. Image (I) produced from scene (S) reflected by a concave mirror*

We then removed a part of each monkey's cortex just in front of the primary visual areas that receive the retinal input and those that regulate the oscillatory movements of the eyes. The monkeys behaved normally on all visual tests except one: now they would pull in the smaller box when it was close while the larger box was far down the alley. At that distance, the larger box made a smaller optical image on the monkeys' retina. The intact monkeys were able to compensate for distance; the monkeys that had been operated upon could not.

When I tell my students about this experiment, I point out that their heads look the same size to me whether they sit in the front or the back row of the room. The students in front did not seem to suffer from hydrocephalus (water-on-the-brain); the ones in back, most likely were not microcephalic idiots.

Constancy in our perception holds within a certain range, a range that varies as a function of distance being observed and the experience of the observer. The range at which a particular constancy ceases forms a horizon, a *background* against which the perception becomes recalibrated. A classroom provides such a "horizon." But out on a highway, automobiles all look pretty much the same size over a longer range in terms of the distance in our field of vision. What determines the horizon in this case is the layout of the road and its surroundings. On a straight road in rolling hills, where distances are truncated by the lay of the land, cars may look small compared to what they might look like at the same distance on a U curve, where the entire road is visible. When there is an unfamiliar gap in visibility, multiple horizons are introduced. The placement of horizons where constancy breaks down is a function of the context within which an observation is occurring.

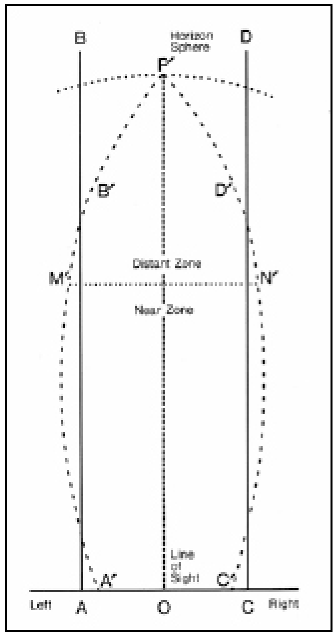
Professor Patrick Heelan, who helps teach my Georgetown class at times, has pointed out that when painters try to depict three dimensions onto a two-dimensional surface, size constancy is limited to a certain range. Beyond that range, other laws of perspective seem to take hold. Heelan is a theoretical physicist and philosopher of science whose specialty is identifying *how* painters construct perspectives that allow us to "see" three dimensions when a scene is displayed on a two-dimensional surface.

On the basis of his 30-year study of paintings and of how we perceive the cosmos, Heelan has concluded that overall visual space appears to us as hyperbolic. For instance, as I mentioned earlier, when we observe objects by looking into a concave mirror—the kind that has a magnification of 7X—objects close to the mirror are magnified in it, but things far away seem to be projected in front of the mirror between ourselves and it—and those objects appear to us smaller than they are when we look at them directly.

Leonardo da Vinci observed that the optics of the eye and the surface of the retina do not compose a flat plane but a hemisphere, thus the physiological process that forms our perceptions cannot be a two-dimensional Euclidian one. Rather, this physiological process forms the concavity of perceived configuration of hyperbolic space. There is a change in the amount of concavity depending upon the distance that is being observed: the closer we focus, the more the lens of the eye becomes bulged; thus there is greater concavity. As our focus become more distant, the lens flattens somewhat, which results ins less concavity. These changes are like changing the magnification of the concave mirror from 7X to 5X and 3X.

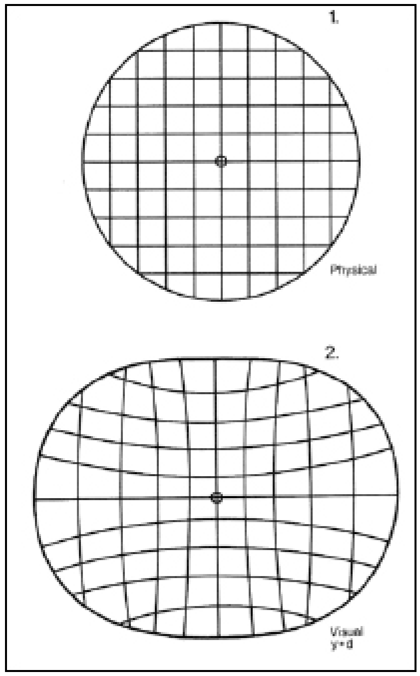
Heelan has proposed that a description of cosmic space as hyperbolic accounts for a good part of the "moon illusion" which occurs when we look at the sun as well. When the moon, or sun, is at the earth's horizon, it appears enormous. Atmospheric haze can add a bit more to this illusion. But as the moon rises, away from our experienced earth-space defined by its horizon, it appears to be much smaller. This change in perception is identical to what we experience when we look at the 7X concave mirror.

Furthermore, when my collaborator Eloise Carlton modeled the brain process involved in viewing the rotation of figures developed by Roger Shepard, my colleague at Stanford, the process consisted of mapping a geodesic path— the shortest route around a sphere—as in crossing the Atlantic Ocean from New York to London via Iceland. Mathematically, this is represented by a Hilbert space of geodesics —a Poincaré group — which is similar to the mathematics used by Heisenberg to describe quantum structures in physics and by Gabor in describing the minimum uncertainty in telephone communications. It is the description of processing by receptive fields that we have become familiar with throughout these chapters.

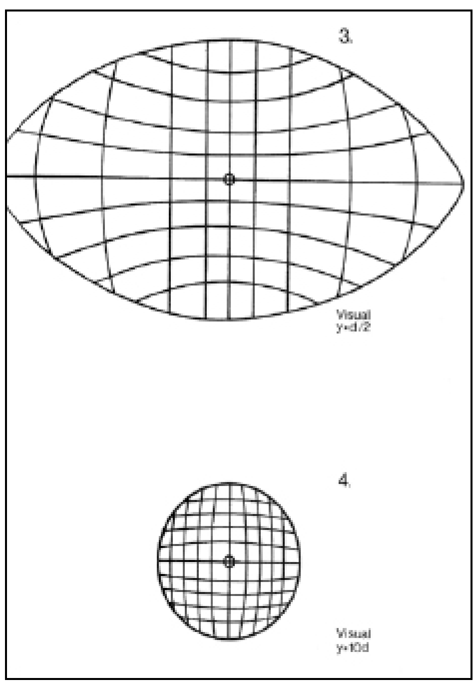



*39. Diagram of a horizontal plane at eye level with two orthogonals AB and CD, to the frontal plane AOC (O is the observer): A'B' and C'D' are the visual transforms of AB and CD in a finite hyperbolic model of visual space. M'N' marks the transition between the near and the distant zones. Contours are modeled on computed values. The mapping is not (and cannot be made) isomorphic with the hyperbolic shapes, but some size and distance relationships are preserved.*

This and similar observations raises the issue as to how much of what we perceive is due to our perceptual apparatus and how much is "really out there." Ernst Mach, the influential early 20th-century Viennese physicist, mathematician and philosopher, whose father was an astronomer, worried all his life about the problem of how much of the apparent size of the planets, stars, and other visual phenomena was attributable to the workings of our perceptual apparatus and how much was "real." Mach's legacy has informed the visual arts and philosophers dealing with perception to this day.




*40. Frontal planes: composite diagram in four sectors: 1. physical frontal plane (FP); visual transform of FP at distance d (near zone: convex); and 4. visual transform of FP at distance 10d (distant zone: concave). d is the distance to the true point for the hyperbolic model. Contours are modeled or computed values for a finite hyperbolic space.*




*41. Diameter of the pattern subtends an angle of 90 degrees with the viewer. B. The diagram is not a set of images to be read visually, but a set of mappings to be interpreted with the aid of the transformation equations: the mappings are not (and cannot be made) isomorphic with the* *hyperbolic shapes, but some size relationships are preserved in frontal planes (or what physically are frontal planes).*

In keeping with the outline presented in the Preface, the perceptions we hold are a consequence of the territory we explore. Within our yards, and within the context of portraying our living spaces onto a two-dimensional surface, Euclidian propositions suffice. When we come to perceive figures that rotate in space and time, higher-order descriptions become necessary. It is these higher-order descriptions that hold when we look at what is going on in the brain. The retina of our eye is curved, and this curvature is projected onto the cortical surface. Thus, any process in the sensory and brain systems that allows us to perceive an object's movement must be a geodesic: a path around a globe.

# The Horizons of Our Universe

Current dogma in cosmology holds that our observable universe began with a "big bang" and is exponentially expanding toward—who knows what? But this is not the only possible interpretation of our observations: Roger Penrose proposes that the technique of "conformal rescaling" which he has so successfully applied to configuring tiles and other perceptual formations can be profitably applied to configuring the form of our observed universe. In doing so, Penrose discerns not a big hot bang at the cosmological origin, but "a pattern like a gentle rain falling on a still pond, each raindrop making ripples which expand and intersect each other." This description is almost word for word the description Leonardo Da Vinci gave some centuries ago and is essentially a description of a holographic process. A rescaling at the horizon of the observed cosmos arrives at a similar holographic pattern.

Two conclusions can be drawn from Penrose's reinterpretation of cosmology:

1. It is *our interpretation* of observations that transforms a perceptual occurrence into a form compatible with the world we navigate. This interpretation is dependent on our human ability afforded by our brain processes.
2. Behind the form we *experience* as the world we navigate is another, a *potential* form that enfolds space, time and (efficient) causality: a

holographic form.

# Chapter 8
## Means to Action

Wherein I distinguish between the brain systems that process muscular contractions, movements, and the actions that give meaning to navigating our world.

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> *The function of the sensory input giving rise to reflex activity . . . is there to modulate the ongoing activity of the motor network in order to adapt the activity (the output signal) to the irregularities of the terrain over which the animal moves. . . . This sensory-motor transformation is the core of brain function, that is, what the brain does for a living.*
>
> —Rodolfo Llinás, *I of the Vortex,* 2001

## At Issue

Navigating the world we inhabit takes a certain amount of skill. The skills we have considered so far are those that allow us to move our sensory receptors in such a way that we can have meaningful perceptions of the world. Philosopher Charles Peirce, being a pragmaticist, noted that what we mean by "meaning" is what we mean to do. To account for our phenomenal experiences, I have added to his statement that meaning also includes the following: what we mean by meaning is what we mean to experience. In both cases "meaning" concerns actions. Brain research performed in my laboratory, and in those of others, has shown us that an act is not as simple as it may seem.

In the early 1950s, I came to study those brain processes that are involved in the control of action. I was faced with a century-long tradition of controversy: Were movements—or were muscles—represented in the brain's motor cortex? Anatomical evidence indicated that fibers from our muscles, and even parts of those muscles, could be traced to the cortex. This kind of representation is also found in the sensory cortex, where specific locations of receptors can be traced to specific locations in the sensory cortex. We call such cortical re-presentations of the geometry of receptors and effectors in humans "homunculi," a term which is discussed in this chapter.

A different view of representation emerges when we electrically stimulate the motor cortex: now we observe contractions of muscle groups. Which groups are activated by this stimulation depends on the position of the limb before stimulation of the cortex is begun. For example, on one occasion, at the Neuropsychiatric Institute of the University of Illinois at Chicago, Percival Bailey and Paul Bucy were electrically stimulating the cortex of a patient, while I sat beside the patient, reporting the resulting movement of this patient's arm. Exactly the same stimulation at the same location produced a flexion of the patient's forearm when his arm was extended, but it produced a partial extension and rotation when his arm started out being flexed. The variations in movements are centered on joints and are produced by transactions among connections centered on the point of stimulation of the patient's motor cortex.

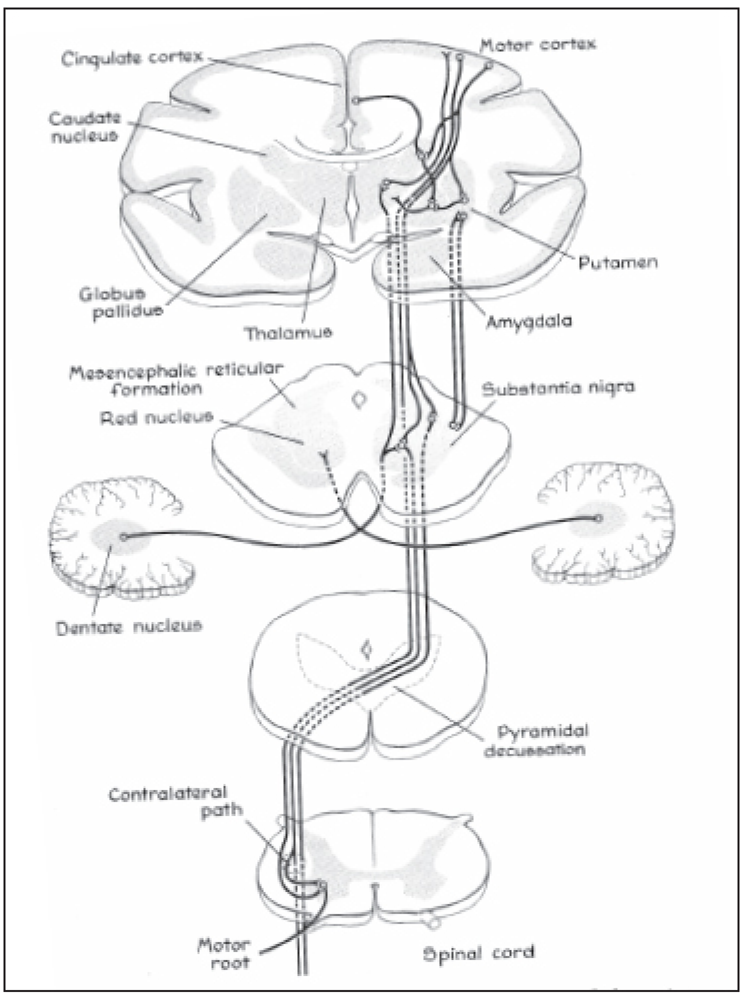
These differences resulting from variations in experimental technique were not recognized as such; instead, they led to that just-mentioned century-long conflict: “Are muscles or movements represented in the brain’s motor cortex?” My interest in this controversy was ignited quite by accident. It took me years to resolve it for myself, yet part of the answer is simple: anatomically, muscles, and even parts of muscles, are connected to the cortex. Physiologically, by virtue of interactions among cortical nerve cells, functions are represented. But my experiments led to yet another level of explanation: behaviorally, actions are represented. The story of how I came to this realization, and how I then reached an explanation of it, is another of those adventures that make discovery so richly rewarding.

In 1950, my colleagues at Yale and I were looking at cortical responses obtained when peripheral nerves were stimulated. At the time, oscilloscopes were not yet available for physiological studies. Fortunately, one of my friends, Harry Grundfest at Columbia University, had gotten the Dumas Company interested in implementing his design for an oscilloscope, and after waiting for about a year, I was the recipient at Yale of the second such instrument (the first went to Grundfest at Columbia, of course). It took my collaborators and me a week or so to find out how to make the oscilloscope work, but finally Leonard Malis, a fellow neurosurgeon with a talent for engineering, helped initiate our first experiment. While he and one of the graduate students, Lawrence Kruger, were setting up, I was in the basement testing the behavior of monkeys in another experiment. When I came on the scene, we had absolutely gorgeous responses on the oscilloscope face: inch-high “spikes” obtained from the brain whenever we stimulated the sciatic nerve of the monkey.

## A Direct Sensory Input to the Motor Cortex

Once over the peak of my elation, I asked where the electrodes had been placed on the brain. The polite answer I received was “On the cortex, you dummy.” I asked where on the cortex—and went to see for myself. What was left of my elation was punctured: the electrodes had been placed on the pre-central gyrus—the motor cortex! The motor cortex was supposed to be an output cortex, not one receiving an input from the sciatic nerve. At the time, and even today, the established idea has been that the nervous system functions much as a reflex arc: an input to a processing center from which an output is generated. I held this same view at the time, so I was understandably upset: These spikes must reflect some sort of artifact, an artificial, irrelevant byproduct of the experimental procedure.

While still observing these spikes, I immediately phoned two friends, experts on stimulating the brain cortex: two neurophysiologists, one at Johns Hopkins University and the other at the University of Wisconsin, Clinton Woolsey and Wade Marshall. Both stated that they had seen this result repeatedly in their experiments using more primitive recording techniques. Woolsey added that he had even published a footnote in the *Proceedings of the American Physiological Society* noting that these "spikes" must be artifacts—that is, not a real finding but an unwanted byproduct of the mechanics (such as a short circuit in the electrical stimulating apparatus) of the procedure. I found this strange: An artifact that is always present and in several laboratories? We were all puzzled.




*42. Diagram of essential connections of the motor system*

Wade Marshall came to the laboratory to see for himself what we were observing. He felt that the "artifact" might be due to a spread of current within the cortex, starting from the sensory cortex to include the motor cortex. Together, we used a technique called "spreading cortical depression" that is induced by gently stroking the cortex with a hemostat. Using this procedure, within a few seconds any neighboring cortically originated activity ceases. The electrical stimulation of the sciatic nerve continued to produce a local brain response, though the response was now of considerably lower amplitude than it had been before stroking the cortex. The remaining response was subcortical, initiated by nerve fibers reaching the cortex prior to our stroking the cortex, which had amplified the response.

So, I asked: If the input from the sciatic nerve is real, what might be the pathways by which its signals reach the cortex? Larry Kruger decided that this would provide him an exciting thesis topic. So, I surgically removed a monkey's post-central cortex—the part of the brain known to receive the sensory input from the sciatic nerve—and therefore a possible way station to the adjacent pre-central motor cortex. The "artifact" was still there.

Next I removed a hemisphere of the monkey's cerebellum, a portion of the primate brain that was known to receive a sciatic nerve input and to provide a pathway to the pre-central motor cortex. Again, there was no change in the "artifact"—the spikes were still there. Finally, I surgically removed both the post-central cortex and the cerebellar hemisphere. Still no change in the response in the motor cortex to sciatic stimulation!

During these experiments, we discovered another puzzling fact. It seemed plausible that some input to the motor cortex might originate in the muscles. But we found, in addition, that stimulation of the sciatic nerve fibers originating in the skin also produced a response in the motor cortex.

Larry Kruger settled the entire issue during his thesis research by tracing the sciatic input directly to the motor cortex via the same paths in the brain stem that carried the signals to the post-central sensory cortex.

The research that I've summarized in these few paragraphs took more than five years to complete. So we had plenty of time to think about our findings.

## What Must Be

What we call the *motor* cortex is really a *sensory* cortex for movement. This conclusion fits another anatomical fact that has been ignored by most brain and behavioral scientists. Notable exceptions were neurosurgeon Wilder Penfield and neuroscientist Warren McCulloch, whose maps of the sensory cortex did include the pre-central region. Their reason was that the anatomical input to the motor cortex arrives there via the dorsal thalamus (*dorsal* is Latin for back, *thalamus* is Latin for "chamber") that is the halfway house of all sensory input to the entire brain cortex except the input for smell. The dorsal thalamus is an extension of the dorsal horn of our spinal cord, the origin of *input* fibers from our receptors, not of *output* fibers to our muscles.

Nineteenth century European scientists had labeled this part of the cortex “motor” when they discovered that electrically stimulating a part of the cortex produced movements of different parts of the subject’s body. When they mapped the location of the cortical origins of all these stimulus-produced movements, the result was a distorted picture of the body, a picture which exaggerated the parts with which we make fine movements, such as the fingers and tongue. Such a map is referred to in texts as a “homunculus” (a “little human”).

While Malis, Kruger and I at Yale were looking at the *input* to the cortex surrounding the central fissure, Harvard neuro-anatomist L. Leksell was looking at the *output* from this cortex. This output had been thought to originate exclusively in the pre-central motor cortex. Now Leksell found this output to originate as well from the post-central sensory cortex. Those fibers that originate in our pre-central cortex were the largest, but the origin of the output as a whole was not limited to these large fibers.

For me, all of these new discoveries about the input to and the output from the cortex surrounding the central fissure called into question the prevailing thesis of the time: that the brain was composed of separate input and output systems. Today, this thesis is still alive and popularly embodied in what is termed a “perception-action cycle.” *However, in our nervous system, input and output are in fact meshed*. The evidence for this comes not only from the brain research conducted in my laboratory, as detailed above, but also from discoveries centered on the spinal cord.

## The Reflex

During the latter part of the 19th century two physiologists, one English, Charles Bell, and the other French, François Magendie, conducted a series of experiments on dogs, cutting the roots of various nerves such as the sciatic nerve. These nerve roots are located at the point where the nerves connect to the spinal cord. Some of the fibers making up these nerves are rooted in the dorsal, or back, region of the spinal cord, the others in the ventral, or ”stomach,” region. When the dorsal fibers were cut off at the root, the dogs had no difficulty in moving about but did not feel anything when the experimenters pinched the skin of their legs with tweezers. By contrast, when the experimenters cut the ventral roots, the dogs' limbs were paralyzed, though the dogs responded normally to being pinched. The results of these experiments are famously enshrined in neuroscientific annals as the "Law of Bell and Magendie."

In the decades just before and after the turn of the 19th to 20th centuries, Sir Charles Sherrington based his explanation of his studies of the spinal cord of frogs on the Bell and Magendie law. It was Sherrington who developed the idea of a reflex—an "input-output arc," as he termed it —as the basis for all our nervous system processing. Sherrington clearly and repeatedly stated that what he called an "arc" was a "fiction," a metaphor that allowed us to understand how the nervous system worked: Reflexes could combine in a variety of ways. For instance, when we flex an arm, contraction of the flexion reflex must be matched simultaneously by a relaxation of the extension reflex; when we carry a suitcase both flexors and extensors are contracted.

These ideas are as fresh and useful today as they were a hundred years ago despite the fact that Sherrington's fiction, of an "*arc*" as the basis for the reflex, has had to be substantially revised.

Unfortunately, however, today's textbooks have not kept up with these necessary revisions. On several occasions, I have written up these revisions at the request of editors, only to have the publishers of the texts tell the editors that the revisions are too complex for students to understand. (I have wondered why publishers of physics texts don't complain that ideas, such as Richard Feynman's brilliant lectures on quantum electrodynamics, are too complex for students to understand.)

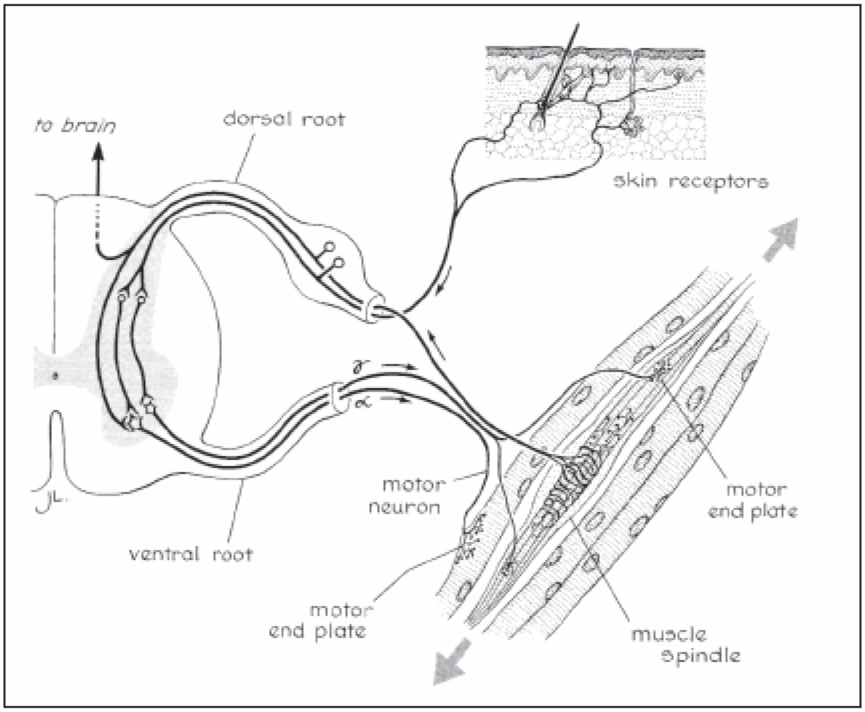
Sherrington's "fiction" of a reflex as a unit of analysis of behavior was the staple of the behaviorist period in psychology. My quarrel is not with the concept of a reflex but with the identification of "reflex" with its composition as an *arc*. The organization of the reflex, and therefore of behavior, is more akin to that of a *controllable thermostat*. The evidence for this stems from research performed in the 1950s that I will describe shortly. The change in conception was from the metaphor of an "arc," where behavior is directly controlled by an input, to a metaphor of a "controllable thermostat," where behavior is controlled by the operations of an organism in order to fulfill an aim. This change has fundamental consequences, not only for our understanding of the brain and of our behavior, but also for society. Doling out charities is not nearly as effective as educating a people, setting their aims to achieve competence.

## How It All Came About

The evidence that produced such a radical shift in the way we view our place in the world was gathered during the 1950s. Steven Kuffler, working in John Eccles's laboratory in Canberra, Australia, had shown that about one third of the fibers in the ventral roots of peripheral nerves—the roots that convey signals to muscles from the spinal cord— end, not in contractile muscle fibers, as had been believed, but in the sensory receptors of the muscles. These are the receptors that respond to stretching of the muscle to which they are attached. The receptor is therefore activated not only to external stimulation that results in stretching the muscle but also to signals coming from the spinal cord. This means that the brain can influence the muscle receptor.

Thus there is no simple way to gauge whether the receptor stimulation is the consequence of *input to our receptors from outside our bodies* or from *input to the receptor originating inside the body*. When we tense our muscles while we are standing against a strong wind, the muscle receptors are influenced in the same way as when we are tense while taking a test. Only some higher-order determination of the origin of the tension would tell us whether the tension was produced externally or internally.

During the remainder of the 1950s, scientists demonstrated this same sort of internal control of receptor function over all receptors except those involved in vision. Powerful internal top-down controls originating in the brain were identified and their effect on the operations of the receptors in the skin, the nose and the ear were studied. We came to know that the body is more than a receiver; it is a receiver that is adjustable to the needs of the body. George Miller, Eugene Galanter and I decided to write a book that showed the relevance of this revised view of receptor function to the field of psychology. *Plans and the Structure of Behavior* is based on the theme that the unit of behavior is not a reflex arc but an input to a "test-operate-test-exit" sequence, a TOTE, which is also the unit that makes up a computer program.




*43. Summary diagram of the gamma (y) motor neuron system. Redrawn after Thompson, 1967.*

# Biological Control Systems

The history of the invention of the thermostat helps make the biological control systems more understandable. During the 1920s and 1930s, Walter Cannon at Harvard University, on the basis of his research, had conceptualized the regulation of the body's metabolic functions in terms of a steady state that fluctuated around a baseline. We get hungry, eat, become satiated, metabolize what we have eaten, and become hungry once more. This cycle is anchored on a base which later research showed to be the organism's basal temperature. He called this regulatory process "homeostasis." A decade later, during World War II, Norbert Wiener, who had worked with Cannon, further developed this idea at the Massachusetts Institute of Technology, where he used it to control a tracking device that could home in on aircraft.

After the war, engineers at Honeywell applied the same concept to track temperature: they created the thermostatic control of heating and cooling devices. In the 1950s, the concept of a thermostat returned to biology, becoming the model for sensory as well as metabolic processing in organisms.

In the process of conducting experiments to find out where such tracking—such controls on inputs—originate, neuroscientists found that, except in vision, control can be initiated not only from structures in our brain stem but also by electrical stimulation of higher-order systems within the brain.

Because our visual system is so important to navigation, I set my Stanford laboratory to work to determine whether or not our brain controls our visual receptors as had been demonstrated to be the case for muscle receptors, touch, smell and hearing. My postdoctoral student Nico Spinelli and I tested this possibility by implanting a micro-electrode in the optic nerve of cats, and then, at a later date, stimulating the footpads of the awake cats, using the end of a pencil. One of us would stimulate the cat's paw while the other supervised the electrical activity recorded from the cat's optic nerve. We obtained excellent responses as shown on our oscilloscope and computer recordings.

We next went on to use auditory stimuli consisting of clicking sounds. Again we were able to record excellent responses from the cat's optic nerve. We were surprised to find that the responses in the optic nerve arriving from tactile and auditory stimulation came at practically the same time as those we initiated by a dim flash. This is because the input to the brain from the tactile and auditory stimulation is much faster than the visual stimuli that have to be processed by the retina. There is so much processing going on in the fine fibers of the retina (recall that there is no nerve impulse rapid transmission within the retina) that the delay in optic stimulation reaching the optic nerve directly is equal to the delay produced by processing of tactile and auditory stimuli in the brain. We wondered whether this coincidence in timing might aid lip reading in the hearing impaired.

When the cat went to sleep, the responses recorded from the optic nerve ceased. Not only being awake but also not being distracted turned out to be critical for obtaining the responses. A postdoctoral student, Lauren Gerbrandt, came to my Stanford laboratory and, excited by what we had found, tried for over a year to replicate our findings in monkeys. Sometimes he obtained the responses from the optic nerve; other times he did not. We were upset and frustrated at not being able to replicate an experimental result that we had already published.

I urged Gerbrandt to choose some other experiment so that he would have publishable findings before his tenure in the laboratory was up. He asked if it would be OK to continue the visual experiments in the evening, and I offered to assist him. He got his wife to help him bring the monkeys from their home cages to the laboratory. The results of the experiments were immediately rewarding. He obtained excellent responses every time, results that I came to witness. But this run of good luck did not last. His wife became bored just waiting around for him and asked if it would be all right for her to bring a friend. Now the responses from the optic nerve disappeared. I came in to witness what was happening and after a few nights the answer became clear to us: We asked the women, who had been chatting off and on, to be quiet. The responses returned. Having established the cause of the variability in the experimental results, we moved the experiment to the room where the original daytime experiments had been performed. Now we found good optic nerve responses whenever the adjacent hall was quiet. When someone in high heels went by, or whenever there was any commotion, the responses disappeared. We had found the cause of the "artifact."

By recording the electrical activity of subcortical structures during the experiment, we were then able to show that the distracting noise short-circuited cortical control at the level of the thalamus, the halfway house of the visual input to the cortex. Thus, we had not only demonstrated cortical control over visual input but had also shown the thalamus to be a necessary brain component involved in the control of the feedback circuitry.

## Controlling the Thermostat

The change from viewing the fundamental unit of behavior as an arc to viewing it as a thermostat-like feedback inspired George Miller, Eugene Galanter and me to write *Plans and the Structure of Behavior* (1960), a book still regarded as seminal to the cognitive revolution in psychology. An anecdote suggests why this is so.

I presented the Sechenov lectures at the University of Moscow during the Soviet period in the 1970s. I. M. Sechenov, for whom the lectures were named, had done for Russian brain science what Sherrington had done in establishing the reflex as the basic unit of behavior. During the discussion period after my lecture, I was asked, "Professor Pribram, did we hear you correctly, did you say you did not believe that the reflex exists?" I answered without hesitation, "No, I did not say that. I presented evidence that the organization of the reflex is not an arc but is more like that of a thermostat."

After the session was over, my host and friend, Alexander Romanovitch Luria, the famous Soviet neurop sychologist, put his arm around my shoulder and said, "Good work, Karl. If you had said that you did not believe in the reflex, you would never have been welcome in the Soviet Union again!" What Luria, Leontiev, the head of Psychology at the Russian Academy of Sciences, and I were trying to accomplish was to move Soviet science from a view based exclusively on Pavlovian conditioning to a stance in which control operations informed and formed the brain, behavior and society. This view had been developed into a field of study called "cybernetics." Some years later—in 1978—Leontiev, in his welcoming address to the International Psychological Congress in Moscow, framed our ideas as being based on reflections rather than on reflexes.

Cybernetics (the art of steering) deals with the way we navigate our world. The brain is conceived as the organ that enables us to steer a steady course that we have decided to set for ourselves. Contrary to the tenets of mid-19th century psychology in the Soviet Union, Europe and elsewhere, we are not totally at the mercy of our environment. It is not an input-output world that we are conditioned to travel. We choose. The world is *meaningful* because we *mean* to choose where, when and how we navigate.

My books *Plans and the Structure of Behavior* (1960) and *Languages of the Brain* (1971) were huge successes in the Soviet Union. Once, the lady in charge of the floor in the hotel where I was staying said she had to see me rather urgently. I wondered what infraction of the many rules I had been guilty of. “No, no. All is well. Would you please autograph my copy of *Languages of the Brain,* which I enjoyed so much, before I go off duty?”

By contrast, in America, *Plans and the Structure of Behavior* received “interesting” reviews. One reviewer remarked that we had written the book in California and had probably suffered sunstroke. Another reviewer was more generous: “Most people do not become senile until they are at least 60,” he stated. “These authors aren’t even 40.”

But one reviewer was helpful: Roger Brown, a noted Harvard linguist, pointed out that our purpose was to show that humans were not just robots at the mercy of the environment but sentient organisms, at least somewhat in control of their fate. Brown indicated that we had perhaps taken a first step, but had not succeeded in our mission.

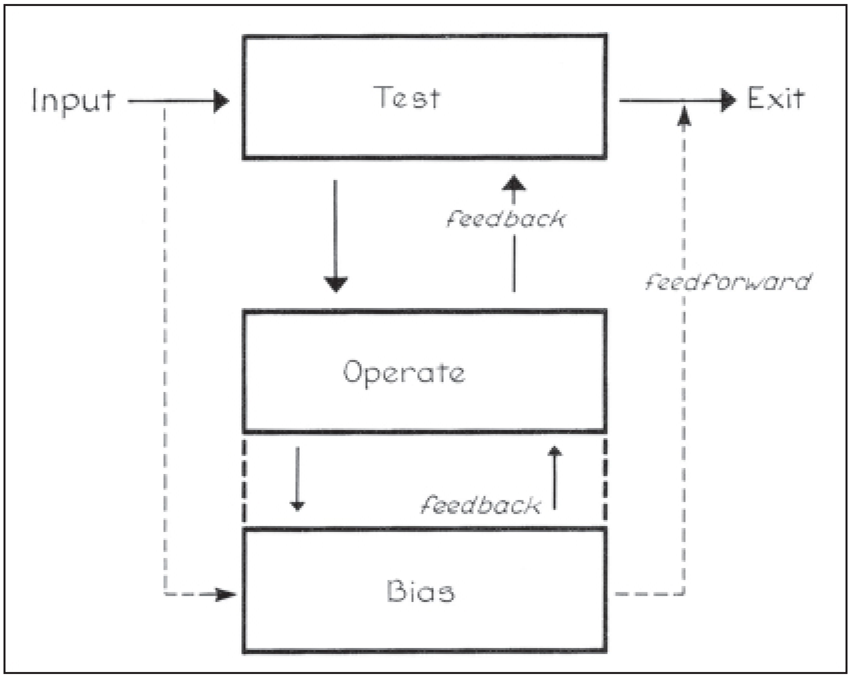
George Miller, Gene Galanter and I had thought that by modeling human planning on a second (the first being the thermostat) metaphor—computer programming—that we had done more than take a first step: Both plans and programs are created before they are actually implemented, and both run their course unable to change as a consequence of being interrupted. If interrupted, they must be started again from the beginning. *But the sensitivity that a great pianist shows when he covers over a small mistake even as it occurs, or the accomplished actor who can cover not only his own missed cues but those of other actors as well, are not the characteristics of computer programs. Accomplished humans do not have to start their performances all over again when some small mistake can be covered by a change in the specifics of the performance.* Something was indeed still missing from our proposal that plans are identical to computer programs.

## Controlling the Thermostatic Control

Over the next decade, a few of us—Hans Lukas Teuber, professor of psychology at MIT; Horst Mittlestedt of the Max Planck Institute at Munich; Ross Ashby of the University of London; and I—discussed this problem on many occasions, and we finally discovered the missing ingredient.

A home thermostat would be too inflexible if it did not have a knob or wheel to set the thermostat's control (technically its set-point) to the temperature we desire. A controllable thermostat allows us to regulate the temperature of a room according to our needs. When the sun sets, the walls of our houses become colder. We begin to radiate the warmth of our bodies toward those walls instead of having the walls radiate warmth to us. *We can change the setting of our thermostat according to our need*. A control such as this operates by adjusting the separation between two wires that close a circuit when they touch. Closing the circuit (a digital—off or on—implementation) turns on the heater or air-conditioner. Ordinarily the separation between wires is maintained and regulated by the amount of heat in the room because the wires expand when heated. The control wheel or knob adds a second factor *working in parallel* with the heat sensitivity of the wires: an "external" factor—the control wheel—operates in parallel to an "internal" factor, the amount of heat in the room.

Roger Sperry and Lucas Teuber named this additional control a "corollary discharge." Actually, the controlling process must slightly precede, that is anticipate, the initiation of movement in order to be effective. Soon, such anticipatory controls were found in the brain. Using microelectrodes, the corollary discharge was seen to originate in the frontal cortex, coincident with the initiation of voluntary eye movements. The controls operate on a group of cells in the brain stem that are adjacent to those involved in actually moving the eyes. Shortly, another experimental result showed that the initiation of all voluntary movement is anticipated by a "readiness potential"—that is, by activity on the medial surface of the frontal cortex just in front of the motor cortex. Using direct current recording, an even earlier electrical change was recorded in the more anterior parts of the frontal lobe.




*44. The TOTE servomechanism modified to include feedforward. Note the parallel processing feature of the revised TOTE.*

The neuroscience community had thus progressed from conceiving of the elementary unit of behavior as a reflex arc to thinking of it as a thermostat-like, programmable process that is controllable from separate *parallel* sources. Even the biological homeostatic process, the inspiration for the thermostat, is now known to be rheostatic (*rheo* is Latin for "flow"), a programmable, *adjustable* process.

Each step of this progression in our thinking took about a decade. But as we shall soon see, even these steps were not enough to fully account for our intrinsic abilities not only to navigate but also to construct the world we inhabit. Now we are finally ready to examine the brain systems that implemented these changes in our views.

## Muscles, Movements and Actions

I return therefore to the controversy that initiated my interest in the motor cortex of the brain: Are muscles or movements represented in the pre-central motor cortex? To find out, I devised a belt with a cuff within which one arm of a monkey could be restrained. Four monkeys so outfitted were each trained to open the lid of a box. The lid had a slot through which a metal loop protruded. A large nail attached to a leather thong was passed through the loop. The monkey had to pull the nail out of the loop and raise the lid in order to obtain a peanut. I timed the duration of the sequence of responses, and my students and I filmed the movements with a time-lapse camera that allowed us to inspect the movements in detail.

After each monkey had reached a stable performance, I surgically removed the entire motor cortex on the side opposite to the hand the monkey was using. I expected that the sequence of movements would be severely disturbed. It was not. All monkeys showed some clumsiness —it took over twice as long for them to retrieve the peanuts —but our film showed no evidence of the monkeys' muscle weakness or any impairment in the sequences of their muscle contractions (that is, of their movements).

As a control procedure, we had originally filmed the monkeys in their home cage, climbing the sides of the cage and grabbing food away from other monkeys. Frame-by-frame analysis of these same acts performed after surgery showed no change in patterns or timing of movements, nor any muscle weakness.

With two additional monkeys, I performed the same experiment after they had been trained to open the box with each hand separately. From these additional monkeys I removed the appropriate cortex on both sides of the brain—both times with the same result.

I need to note again an important point about the surgery. The cortex was removed with a fine tube through which suction could be applied. The amount of suction was controlled by a small thumbhole near the held end of the tube. The gray matter, composed of the cell bodies of neurons, can be removed with this instrument without damaging the underlying stiffer white matter, which is composed of nerve trunks that connect different parts of the cortex to each other and to subcortical structures. The damage produced by removing only the gray matter is local, whereas damage to the white matter produces more serious disabilities because more distant regions become involved. The brain damage produced in patients by strokes or accidents always includes the brain's white matter.

## The Act

I came to understand the distinction between movement and action as a result of these experiments with monkeys, experiments that were undertaken at the same time as those in which we stimulated the sciatic nerve. *The motor cortex turned out to be not only a sensory cortex for action—an act turned out to be more of a sensory accomplishment than a particular set of movements*.

Behaviorally, the motor cortex is not limited to programming muscle contractions or movements. This cortex is involved in making actions possible. *An act is a target, an attractor toward which a movement intends*. I illustrate this for my classes by closing my eyes, putting a piece of chalk between my teeth, and writing with it on the blackboard. It matters not whether I use my right hand or my left, my feet or my teeth—processes in my motor cortex enable what becomes written on the board. What is written is an achievement that must be imaged to become activated. Such "images of achievement" are the first steps leading to action, whether literally, as in walking, or at a higher, more complex level as in speaking or writing.

The answer to the initial question that started my research on the motor cortex can be summarized as follows: anatomically, muscles are represented in the motor cortex; physiologically, movements around joints are represented there. Behaviorally, *our cortical formations operate to facilitate our actions*. How?

For ethologists—zoologists studying behavior, as for instance Konrad Lorenz and Niko Tinbergen—the study of behavior is often the study of particular movements, the fixed patterns of a sequence of muscle contractions made by their subjects. Their interest in neuroscience has therefore been on the spinal and brain stem structures that organize movements.

By contrast, my interest, stemming from the experiments on the motor cortex, has been in line with the behaviorist tradition of psychology, where behavior is defined as an action. An act is considered to be the environmental outcome of a movement, or of a sequence of movements. B. F. (Fred) Skinner remarked that the *behavior* of his pigeons is the *record* made when they pecked for food presented to them according to a schedule. These records were mainly made on paper, and Skinner defined behavior as the paper records that he took home with him. They were records of responses, and Skinner was describing the transactions among these responses: he described which patterning of responses led to their repetition and which patterns led to the responses being dropped out. The interesting question for me was: What brain processes are entailed in these transactions?

An anecdote highlights my interest. The United Nations University hosted a conference in Paris during the mid-1970s. Luria, Gabor and other luminaries, including Skinner, participated. In his address, Skinner admitted that indeed he had a theory, something that he had denied up to that time. He stated that his theory was not a stimulus-response theory nor was it a stimulus-stimulus theory; his theory was a response-reinforcement theory. Furthermore, he stated, reinforcement was a process. I felt that he had given the best talk I'd ever heard him give and went up to congratulate him. Skinner looked at me puzzled: "What did I say that makes *you* so happy?" I replied, "That reinforcement is a process. The process must be going on in the brain." I pointed to my head. Skinner laughed and said, "I guess I mustn't say that again." Of course he did. In 1989, a year before he died, he wrote:

> *There are two unavoidable gaps in the behavioral account: one between the stimulating action of the environment and the response of the organism and one between consequences and the resulting change in behavior. Only brain science can fill those gaps. In doing so it completes the account; it does not give a different account of the same thing.*

## Reinforcement Revisited

Skinner's contribution to the nature of reinforcement in learning theory has not been fully assimilated by the scientific and scholarly communities: Skinner and his pupils changed our conception of how learning occurs from being based on pleasure and pain to a conception based on self-organization, that is, on the consequences produced by the behavior itself. Pavlov's classical conditioning, Thorndike's "law of effect," Hull's "drive reduction" and Sheffield's "drive induction"—even the idea that interest is some sort of drive—are all different from what Skinner's operant conditioning revealed. In my laboratory, a colleague and I raised two kittens from birth to demonstrate the self-maintenance and self-organizing aspects of behavior. We nurtured one kitten with milk on its mother's breast; we raised a littermate on the breast of a non-lactating cat and fed the kitten through a stomach tube. After six months, there was practically no difference in the rate of sucking between the two kittens. Mothers who have tried to wean their infant from sucking on his thumb or on a pacifier might feel that such an experimental demonstration was superfluous.

The change in conception of reinforcement from being based on pleasure and pain to being based on performance per se is important for our understanding of human learning. Rather than rewarding good behavior or punishing bad behavior, operant behaviorism suggests that we "educate" (Latin *e-ducere*, "lead" or "draw out") a person's abilities— that we nourish the performances already achieved and allow these performances to grow by leading, not pushing or pulling. In these situations, *pleasure is attained by achievement; achievement is not attained by way of pleasure*. I did not have to look at my score sheets to find out whether my young male monkeys were learning a task: their erect penises heralded their improvement—and conversely, when their performance was lagging, so was their penis.

My good students have used a technique that I used in college. We review and reorganize our notes about once a month, incorporating what we have learned that month into our previous material. A final revision before the final exams relieves one of useless night-long cramming. I say useless because crammed rote learning needs much rehearsal—as in learning multiplication tables—to make a lasting impression. What has been learned by cramming is well forgotten by the next week.

## More to Be Explained

The results of my experiments on the motor cortex, and the conclusions based on them, were published in the 1950s while I was still at Yale. Our results were readily accepted and even acclaimed: John Fulton, in whose laboratory I conducted these studies, called the paper "worthy of Hughlings Jackson," the noted English neurologist whose insights about the functions of the motor cortex were derived from studying epileptic seizures.

My conclusions were that the removals of motor cortex had produced a "scotoma of action." In vision, a scotoma (from the Greek scotos, "darkness") is a dark or blind spot in the visual field. In Chapter 6 we reviewed the evidence that some patients can reasonably well navigate their blind visual field despite being consciously “blind” within that dark spot or field. The scotoma of action produced by my removals of the motor cortex had a similar effect: the monkeys’ difficulty was restricted to a particular *task*, though they could still perform that task with some loss of skill, as demonstrated in film records of their behavior and by the longer time it took them to reach the peanut in the box. In my experiments the “scotoma of action” referred to a particular task rather than to a particular area of perceived space as in vision—and not to a difficulty with any particular muscle group or a particular movement.

Today a great deal has been learned regarding the specific targeting of an action. Much of the experimental and clinical research has been performed on “visuomotor” achievements such as grasping an object. The brain cortex that has been shown involved lies somewhat behind and in front of the cortex surrounding the central fissure, the cortex involved in the experiments on primates reviewed above. This may well be because in primates the central fissure has moved laterally from its position in carnivores, splitting the visuomotor related cortex into parietal and frontal parts.

# The How of Action

Despite the acclaim given to the results of my early experiments, they gave me a great deal of trouble: I could not envision a brain process that would encode an act rather than a movement. Lashley had noted the problem we must face when he described the instinctive behavior of a spider weaving a web. Essentially, the same pattern is “woven” in various environments that may be as diverse as the regular vertical posts on our porch or the forked branches of trees. Technically, this phenomenon is called “motor equivalence” and the issue troubled us because we could not imagine any storage process in the brain that might result in virtually identical behaviors under many diverse circumstances. In humans, motor equivalence is demonstrated when we write the same message on a horizontal or on a vertical surface, or even in the sand with the toes of our left foot. Many of the actual movements involved are different.

Some seven years passed after the publication describing our experiments on the motor cortex. During that time, I continued to be at a total loss for an explanation. I kept searching for a clue as to how a "scotoma of action" might have been produced by my experiments.

A series of fortunate circumstances provided the answer. In the mid-1970s, while I was lecturing at the University of Alberta, interaction with the university's professors provided a most enriching experience. These discussions were enhanced by talks about realism with Wolfgang Metzger, an influential psychologist from Germany who sharpened my views on how our brains contribute to navigating the reality of the world we perceive. Much of this chapter is framed within the conclusions I reached at that time.

As noted in Chapter 5, James Gibson, professor at Cornell University famous for his experiments and ideas on visual perception, visited Alberta for prolonged periods while I was there, and we discussed in depth a number of issues regarding his program that came to be called "ecological perception." Gibson was calling attention to various aspects of the environment, such as horizons and shadows, that determine our perceptions. In terms of Metzger's realism, I agreed with all that Gibson was saying; but at the same time I also insisted that specific brain processes were necessary to "construct" what we perceive: that ecology extended inside the organism as well as outside.

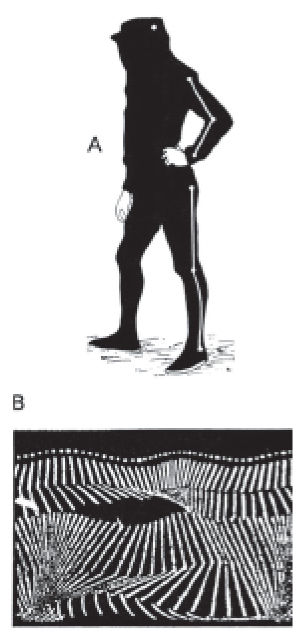
There was good reason for Gibson's stance. Cornell had been the central bastion of introspective psychology in America. Introspective psychology was founded on the technique of asking people what they saw, heard, felt or thought. Behaviorism reacted against introspective psychology because, using the technique of asking for answers, psychologists had great difficulty in confirming, between subjects and even in the same subject, answers to questions asked. This was no way to construct a science of psychology. Gibson, who had been a pupil of E. B. Tichner, the towering figure and promulgator of introspection, had rebelled against introspection just as thoroughly as had those psychologists who were studying behavior. Gibson's experimental approach to perception displayed figures on oscilloscope screens and specified the changes in the display that resulted in changes of perception. Shortly, we will see the power of this approach in resolving the issue about the very functions of the motor cortex that were puzzling me.

# A Fortuitous Return to the Motor Cortex

It was Sunday morning of my last week of lectures in Alberta, and I had been asked to talk about the “motor systems” of the brain. I agreed and added that there were some problems that perhaps the participants could help me resolve.

I’m an early riser. What to do on a Sunday morning? I started to make notes for my lecture: “The Motor Cortex.” Twenty minutes later I threw the blank sheet into my wastebasket. Another blank sheet: “The Motor Systems of the Brain.” Another twenty minutes. Into the basket. After an hour or so, I gave up. As I was leaving in a week, I could usefully pack books that I would not need anymore and ship them home.

While packing, I came across a translation from Russian of a book by Nikolas Bernstein, whose work had been highly recommended to me by Alexander Romanovich Luria at a dinner in Paris. I had skimmed the Bernstein book at least twice and had found it uninteresting. With regard to brain function, Bernstein’s insight was that whatever the brain process, it was nothing like the process of our experience. Not exactly a new thought for me. But I was to see Luria soon—so what could I say to him? I sat down to read the book once more and tried to pay special attention to the behavioral experiments that Bernstein had carried out. There might be something there that I had missed.



*45. (a) Subject in black costume with white tape. (b) Cinematograph of walking. Movement is from left to right. The frequency is about 20 exposures per sec. Reprinted with permission from N. Bernstein,* The Co-ordination and Regulation of Movements. *© 1967 Pergamon Press Ltd.*

# Eureka!

In Bernstein's experiments, he had dressed people in black leotards and filmed them against black backgrounds, performing tasks such as hammering a nail, writing on a blackboard, or riding a bicycle. He had taped white stripes onto the arms and legs of the experimental subjects. In later experiments, Bernstein's students (and, as previously discussed, Gunnar Johanssen in Sweden) placed white dots on the joints. After developing the film, only waveforms made by the white tapes could be seen. Bernstein had used a Fourier procedure to analyze these *waveforms* and *was able to predict each subsequent action accurately!!!*

I was elated. This was clear evidence that the motor system used essentially the same procedures as did the sensory systems! My seven years' hunt had ended. I gave my lecture on the brain's motor systems the next day and was able to face Luria with gratitude the following week.

# The Particular Go of It

Next, of course, this idea had to be tested. If processing in the motor cortex were of a Fourier nature, we should be able to find receptive fields of cortical cells that respond to different frequencies of the motion of a limb.

An Iranian graduate student in the Stanford engineering department, Ahmad Sharifat, wanted to do brain research. He was invaluable in upgrading and revamping the computer systems of the laboratory as well as in conducting the planned experiment.

A cat's foreleg was strapped to a movable lever so that it could be passively moved up and down. We recorded the electrical activity of single cells in the motor cortex of the cat and found many cells that responded primarily, and selectively, to different frequencies of motion of the cat's limb. *These motor cortex cells responded to frequencies much as did the cells in the auditory and visual cortex.* The exploration had been successfully completed.

## Fixed Action Patterns

My experimental program had resolved the issue of what the primate motor cortex does. I had also been able to show how the doing, the action, is accomplished. But, as yet, I had not created a precise formal description of what actions do for *us*. The solution to this problem came from the work of Rodolfo Llinás, professor of neurophysiology at the medical school of New York University.

Sherrington had had the wisdom to note that his "reflex arc" was a fiction, a wisdom not shared in current texts. One reason for Sherrington's insightful approach might have been a critique by the English neurologist Graham Brown (no relation to Roger Brown). Brown observed that dogs showed no difficulty in walking despite having their dorsal roots severed. In today's terms, their locomotion appeared to be "preprogrammed."

Rodolfo Llinás, in his book *I of the Vortex,* expresses a view complementary to mine regarding what the brain does. Llinás takes the view expressed by Graham Brown, instead of that proposed by Sherrington as his starting point. Brown had emphasized the fact that cutting the sensory roots of peripheral nerves leaves an animal's movements intact. Llinás calls the units of behavior based on Brown's insight "fixed action patterns." The virtue of such patterns is that they anticipate "the next step" as they become actualized. As I walk, my next step is anticipated as I lift my foot during the current step. This aspect of behavior cannot be accounted for by Sherrington's reflex arc but can readily be handled by the change of metaphor to the controllable thermostat.

But fixed action patterns encounter their own set of difficulties: I helped fund a series of experiments in which sensory roots were cut over a much greater extent than in Graham Brown's experiments. In those experiments, though gross movement was still possible, it was seriously impaired and learning a skill was absent. At a larger scale, fixed action patterns by themselves do not account for our behavior.

## A Generative Process

At these higher levels, Llinás brings in sensory processing. Recall that, in order to account for our ability to perceive images and objects, movements are necessary: that in vision, nystagmoid movements are necessary to perceiving images; and that more encompassing movements are necessary for us to perceive objects. The result of movement is to make some aspects of the sensory input “hang together” against a background, as in Johanssen’s *grouping* of dots. This hanging together, or grouping of sensory inputs, is technically called “*co*variation.” Llinás brings in covariation among sensory patterns to fill out his view.

Furthermore, Llinás also describes the encompassing organizations of fixed action patterns, our movements, as “hanging together” much as do sensory patterns. As described in Chapter 6, the hanging together of action patterns is described as “*contra*variation.” The difference between covariation in sensory patterns and contravariation in action patterns is that contravariation implies the anticipatory nature of action patterns.

When covariation and contravariation are processed together, the result *generates* our perception of objects (Chapter 6) *and our accomplishment of acts*. Technically *the “coming together” of covariation and contravariation produces invariances. Objects are invariant across different profiles—that is, across different images of the sensory input—while acts are invariant across different movements that compose an act*.

Finally, the research on cortical processing of visuo-motor acts accomplished by Marc Jeannerod and comprehensively and astutely reviewed in *Ways of Seeing* by him and Pierre Jacob, provides the specificity required by the actions guided by their targets, their images of achievement. These experiments deal with invariants developed by the transactions between actions and the images upon which they intend to operate.

Viewing acts as invariants composed across movements and their intended achievements is the most encompassing step we have reached in our understanding: brain processes that enable meaningful actions—we have moved from reflex arc, through controllable thermostat, to what can be called a *generative organization* of the brain/mind relationship.

This generative organization can be understood as being produced by “motor inhibition” by analogy to the process of sensory inhibition. In Chapter 5, I reviewed Békésy’s contribution on sensory inhibition that showed how our perceptions are projected beyond ourselves. For the generative motor process, we can invoke motor inhibition to internalize (introject) our images of achievement, the targets of our actions. When, for instance, we write with our pens in our notebooks or type on our computer keyboards, we produce an achievement. This achievement must be internally generated in some fashion, and motor inhibition can fulfill this role. Massive motor inhibition is produced by the cellular interactions among their fine-fiber connections in the cerebellar hemispheres: Purkinge cells release GABA, which produces a feedforward inhibition. Other cells (basket and stellate) can inhibit the Purkinje cells. Thus multiple stages of inhibition can *sculpt* the target—form the achievement.

## Imitation and Imagination

In our book *Plans and the Structure of Behavior,* we refer to several different sorts of Plans. Some we call "tactics." John Searle has called these "intentions-in-action." In primates, including humans, such tactics are controlled by systems involving the "motor and sensory cortex" of the pre- and post-central gyrus (discussed in Chapter 5). We also identified the anterior, the pre-frontal cortex, as being involved in the initiation of longer-range "strategies," Sear-le's "prior intentions." Current brain-imaging techniques are validating these earlier conclusions that were based on evidence obtained from brain injuries and electrical recordings and stimulations. Intentions are attractors, targets— "images of achievement."

For the past decade, scientists have been documenting the existence of "mirror processing" in the brain. These experiments have shown that many of the same brain cells and brain regions are active under several related circumstances: when an action is undertaken; when that action is imagined but not undertaken; and when the person or animal is watching someone else perform the same act. These results are extremely important for comprehending how we understand each other—for empathy and for our ability to anticipate each other's intentions.

Initially these experimental results were restricted to Broca's area—the part of the frontal lobe of the brain that was believed to be involved in the expression of speech— and to a separate area in the inferior parietal (back) part of the brain. But as my colleagues and I had demonstrated back in the 1960s, by comparing the arrangement of thalamo-cortical connections between carnivores and primates, these two parts of the brain, front and back, are really one, and have been split apart in the primate brain by the intrusion of the primary sensory-motor cortex that surrounds the central fissure. More important, mirror processing has been shown to occur in other parts of the frontal cortex, depending on what is being mirrored or imagined—for instance, a skill or an emotional attitude.

As with most of today's brain research, such important results fill an aspect of the brain/behavior/experience gap by way of correlations. In themselves, they do not provide a possible "mechanism" for *how* these brain processes operate. The evidence (reviewed in the present chapter) that leads to the conclusion that *acts* are based on environmental targets does provide such an explanation. Intentions, imitations and imaginings all share the attribute of projection; that is, they adapt our actions to "realities" in the environment by actively selecting and *incorporating* sensory input. The research that explored the basis for "images of achievement" therefore goes a step further than the discovery of "mirror neurons" in specifying a possible (probable?) process by which such "mirrors" can be achieved.

When I first visited the Soviet Union, I imagined what living in a communist country would be like. I found, much to my surprise, that the Soviets actually dealt with "filthy lucre" (money) and even had savings accounts! This and other, less dramatic surprises changed my trans-acting the daily process of getting from one place to another, of obtaining revenues from translations of my books, and of paying bills at restaurants, incorporating the financial aspects of the Soviet system into my actions. After a while, I could imagine and project in further transactions what my hosts would be requiring. *Note that this sequence is not a perception-action sequence; it is an incorporation of perception to modify ongoing action and an incorporation of action into an ongoing perception.*

The attractor, the target, the achievement, in these situations is imagined. In other situations the target is imitating another person as babies do when playing peek- a-boo. The Fourier-like process, in the richness of its processing and storage capacity, furnishes a viable (neuro-nodal) medium within which the brain can proficiently organize the skills that form our actions, imaginings and imitations.

## Speaking

The discovery that our human brain's motor cortex encodes achievement—not movement per se—has signifi-cant import for our understanding of language.

One theory of how our speech develops suggests that a baby's babbling gradually, through practice, allows the emergence of words and sentences. This is called the "motor theory of language production." Speaking, when regarded as a skill, makes such a theory plausible. However, linguists have expressed a considerable amount of skepticism, based on their observations of the development of language in infants.

I vividly remember discussing this issue with Roman Jakobson, dean of classical linguistics at Harvard, with whom I worked repeatedly in venues as far apart as Moscow, the Center for Advanced Studies in Palo Alto, and the Salk Institute in LaJolla, California. Jakobson pointed out to me what is obvious: a child's development of his ability to understand language precedes by many months his ability to speak. Also, once the ability to speak emerges, and a caretaker tries to mimic, in baby talk, the child's erroneous grammatical construction, the child will often try to correct the adult. These observations indicate that the child has a much better perceptual grasp than a motor performance ability in the use of language.

The motor theory of language can be reinstated, however, when we conceive of language as a "speech act," as John Searle, the University of California at Berkeley philosopher, has put it. According to my research results reviewed in this chapter, the motor systems of the brain encode "acts," not movements. In this regard, speech acts become achievements, targets that can be carried out with considerable latitude in the movements involved. Perception of the target *is* the essence of the execution of an act, including the act of speaking. Babies learn to *target* language before they can comprehensibly speak it. The outdated "motor theory" of speech needs to be reformulated as an *"action theory" of speech*.

Linguist Noam Chomsky and psychologist George Miller each have called our attention to the fact that we can express (achieve) as speech acts the same intended meaning in a variety of grammatically correct ways. Chomsky has developed this observation as indicating that there is a deep, as well as a surface, structure to language.

I extend Chomsky's insight to suggest that *the variety of languages spoken by those who know several languages provides evidence for the existence of an ultra-deep language process. This ultra-deep structure of language processing occurring in the brain does not resemble the surface* *expressions of language in any way*. I will consider this view more fully in Chapter 22.

## In Summary

*Our brain processes are not composed of input-output cycles. Rather, they are composed of interpenetrating meshed parallel processes: the motor systems of our brain work in much the same way as do our sensory systems. Our sensory systems depend on movement to enable us to organize the perception of images and objects. Conversely, our brain's motor systems depend upon imaging the intended achievement of our actions.*

*Objects remain invariant, constant, across the variety of their profiles—the variety of their images. Actions remain invariant across the variety of movements that can produce them. Speech acts, intended meanings, are invariant not only across a variety of expressions but also across a variety of languages.*

# A World Within

# Chapter 9
## Pain and Pleasure

Wherein the rudiments of the “form within” that initiate pain and pleasure are shown to derive from stem cells lining the central cavities of the brain. Pain is shown to be homeostatically controlled. And a much-needed physiological explanation for the generation of pleasure is developed.

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*We’re having a heat wave,*
*A tropical heat wave,*
*The temperature’s rising,*
*It isn’t surprising*
*She certainly can can-can.*

—Marilyn Monroe singing “Heat Wave” *in There’s No Business Like Show Business,* 1954. Lyrics by Edward Holland, Jr., Lamont Herbert Dozier and Brian Holland.

So far, I have dealt with our direct relationship with the world we navigate. Targets and intentions characterize this relationship, which is executed by output to muscles and mediated by input from sensory receptors. I have also noted that this relationship occurs within a context. The context comes in two forms: the inner world of our bodies and the social world of communication and culture.

The questions asked in this chapter deal with the inner world of our bodies: What is the brain physiology of pain? And of persistent suffering? What is the brain physiology of pleasure? There were few answers to these questions when I began my research. In 1943, I asked Percival Bailey, the classifier of brain tumors with whom I had received a fellowship, what I might read. His brief answer was: "There is nothing."

In the mid-1950s, Jerry Bruner invited me to teach a session in his Harvard class. He started the class by asking me what my research goals were. I answered that I would like to know the brain underpinnings of emotion as clearly as (I thought I knew) those that organize our perceptions. I had already begun the relevant research at Yale, but those results had not become integrated into my (or the establishment's) understanding. For the most part the terms "feelings," "emotions," and "motivations" were used interchangeably. "Pain" was identified with mild electric shock that produced aversive behavior and "pleasure" with morsels of food that evoked approach. The neurophysiology of pain was in doubt, and no one even dared think about what the brain physiology of pleasure might be.

I did pay heed to William James's visceral theory of emotions despite Walter Cannon's and Karl Lashley's critiques; I discussed the theory with Wilder Penfield, who stated that he had occasionally produced heart-rate changes when he electrically stimulated the region of the anterior insula of the brain. I knew of von Economo's and also of Papez's proposals that the hippocampal-cingulate cortex circuit was anatomically suited to deal with the circularity and persistence of emotions. And there were the experimental results of Paul Bucy and Heinrich Klüver who showed that bilateral removal of the entire temporal lobe produced tame monkeys. But during the mid-1940s, when my research began, none of this had been put together in any orderly way—nor had we evidence to test the anatomical proposals of von Economo and Papez, or to take the Klüver-Bucy findings further.

The following chapters chart the voyage of discovery that I undertook to clarify, for myself and for the scientific and lay community as a whole, what the relationship between feelings, emotions, motivations, pain and pleasure might be. The course was not always straightforward: there were storms and calms. In order to recount these in any readable fashion, I start with pain and pleasure.

The stories that have unfolded about how these discoveries were made, and to which I have had the opportunity to contribute, are as exciting as those that I read as a child. Paul DeKruif's *Microbe Hunters* told about the discoveries made by scientists who were my father's contemporaries and whose work helped him classify bacteria and fungi. Also the explorations of Admiral Byrd, whose book on Antarctica I read at least a dozen times when I was ten years old, made me wonder what comparable territory was left for me to explore: that territory turned out not to be "out there," but within our heads.

I was especially pleased, therefore, when Paul MacLean, who had been my colleague at Yale, dedicated to me the translation into English he had inspired, of a book written by Ramón y Cajal, one of the eminent pioneers to describe the shape of brain cells. The dedication read: "To Karl Pribram, Magellan of the Brain."

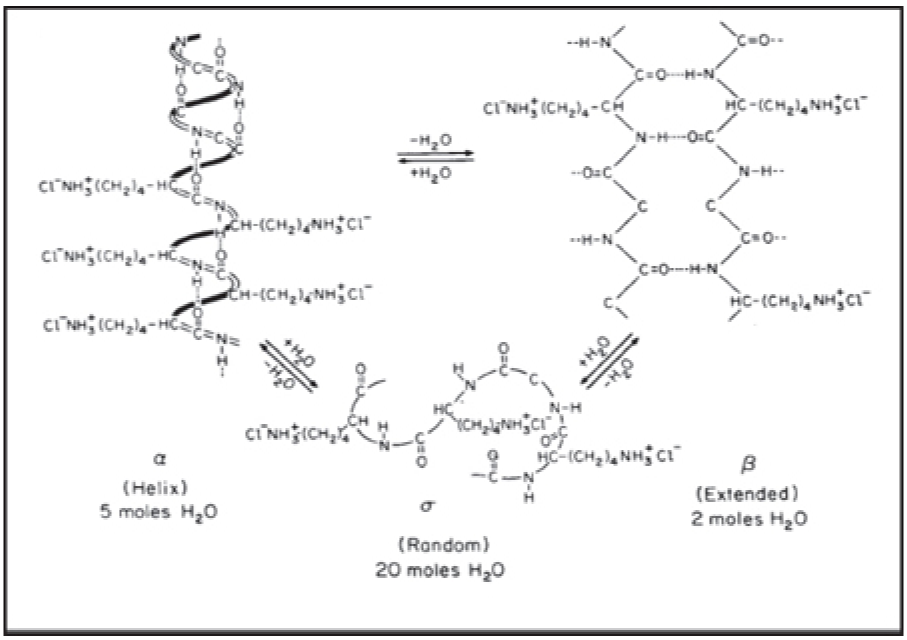
The inner world within which targets and intentions are pursued is referred to as "motivation." Sometimes the term refers simply to the fact that we are alive and eagerly navigating our world. A more important use of the term "motivation," which is developed in the next chapter, is akin to its use in music where "motif" describes a pattern that forms the theme that unites the entire enterprise.

In describing the brain organizations that form our world within, I will follow the theme, the "motif" that permeates this book: I compare contexts that are *shaped* with those that are *patterned*. Essentially, the "world within" is "shaped" by its chemistry; brain processing provides its "patterns."

## Shaping the World Within

Organic chemistry is a chemistry of shapes. Bonds, shaped by valences (possible combinations), connect parts of molecules whose form determines their function. Large molecules, such as proteins, can change configuration with the displacement of an atom, such as hydrogen, to alter the protein's function.

As a prelude to tackling the brain processes that deal with pleasure and pain, I will describe a most interesting proposal regarding shape in "membranes," the substrate on which the patterns of pain and pleasure operate. As in the case of perception and action, we are faced with a surface and a deep process: but for the world within *it is the chemistry that furnishes the deep process and the patterns dealing with feelings and choice that form the surface structure*.

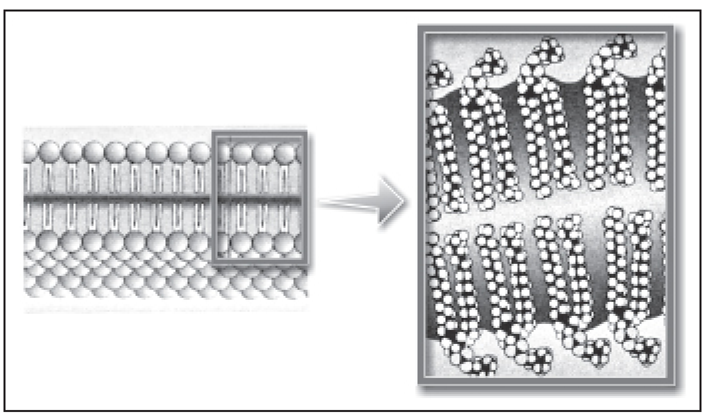



*46. Changes in the conformation of an amino acid under different contexts provided by H20.* Languages of the Brain*, 1971*

## A Membrane-Shaping Process

Even water changes its properties by changing its form. A simple but revolutionary example of the importance of shape in chemical processing comes from a suggestion as to how water, when its H2O molecules become aligned, becomes superconductive. My colleagues and I, as well as others, such as I. Marshall in his 1989 article "Consciousness and Bose-Einstein Condensates," have proposed that the membranes of cells such as those of the stem cells lining the cavities of the brain can organize the configuration, the shape, of water. The membranes are made up of phospholipids. The lipid, fatty part of the molecule is water repellant and lies at the center of the membrane, giving it structure; the phosphorus part forms the outer part of the membrane, both on the inside and outside, and attracts water. The phospholipid molecules line up in parallel to compose the linings of the membrane. Gordon Shepherd, professor of physiology at Yale University, has described the water caught in the interstices of the aligned phosphorus part of the membrane as being "caught in a swamp." My colleagues, anesthesiologist Mari Jibu, physicist Kunio Yasue, the Canadian mathematician Scott Hagen and I ventured to suggest that the water in the swamp becomes "ordered;" that is, the water molecules line up much as they do in a meniscus at a surface. Ordered water forms a "superliquid": superliquids have superconducting properties. Such properties are not constrained by the resistance produced by ordinary materials.

In our work, we speculated that these membrane processes might serve as substrates for learning and remembering. As such, they may do this, in the first instance, by ordering the membranes involved in the most basic components of learning and remembering: the processing of pain and pleasure. These are the membranes of stem cells lining the central cavities of the brain that actually provide a most effective substrate for experiencing pain and pleasure.



*47. Phospholipid membrane of dendrites (From* Neurobiology *by Gordon M. Sheperd)*

# Core-Brain Pattern Sensors

In describing the context within which we navigate our world, scale is an important consideration. Overall, at a large scale, as long as we are alive, as animals we strive to move. Movement has consequences. Some consequences make us move more, some make us move less. Movement itself uses energy, and one of the ways we can sense the depletion of energy is that we feel hungry. When we are hungry, we move more; having eaten, we move less.

We describe changes in the depletion and restoration of our energy in terms of the body's metabolism. Tracking metabolism requires sensors, sensitive to various metabolic *patterns*. Some rather exciting experiences introduced me to these sensors; they line the most interior parts of the brain.

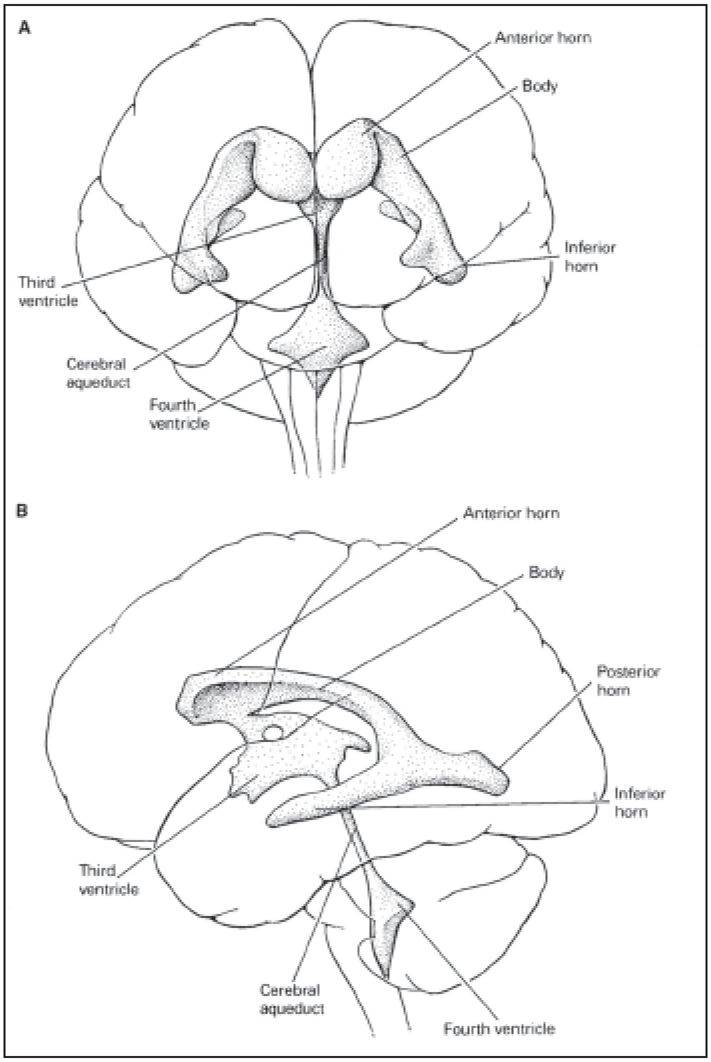
In the early 1940s, as his resident in neurosurgery, I was assisting Paul Bucy and his mentor, Percival Bailey (who had worked for a decade and a half with Harvey Cushing, the first neurosurgeon in America) at the Neuro-psychiatric Institute of the University of Illinois at Chicago to perform a delicate surgical procedure. Under local anesthesia, we had opened the back of the our patient's skull to gain access to the auditory nerve with the purpose of curing her Ménière's disease, a persistent ringing of the ear accompanied by occasional vertigo (spinning dizziness). Cutting into the auditory nerve reduces and often entirely abolishes the intolerable symptoms. The brain stem (an extension of the spinal cord that enters into the skull) and part of the cerebellum were exposed to view. During surgery it is customary to keep the exposed brain wet by squirting it with a dilute salt solution. The concentration of salt is the same as that in the body fluids, including the cerebrospinal fluid that bathes the brain and spinal cord.

On this occasion, every time we squirted the liquid onto the brain the patient, who, was awake, would complain. The brain itself is insensitive; only on the rare occasions when it becomes necessary to pull on blood vessels does the patient feel uncomfortable. So we were surprised that the patient had felt anything at all. We thought perhaps there was an aberrant blood vessel in the way, but there wasn't. Squirt. Again the patient complained. Another squirt and the patient felt nauseated: we certainly did not want her to retch, which would put pressure on the exposed brain and might dislocate parts of it.

The squirt was clearly the cause of her discomfort. We asked our scrub nurse whether she was certain that the liquid she had given us to squirt was the correct one. She assured us that it was: she had personally found doubly distilled pure sterile water for the surgery. "DISTILLED WATER! How could you?" Unless the correct amount of salt is in the solution, distilled water is an irritant to delicate tissue such as the stem-cell membranes lining the ventricles. Recall that these membranes are dependent for their function on the ordering of their "water," which is imbedded in the appropriate saline solution.

The offending distilled water was quickly replaced, and the surgery proceeded without any further hitch and with excellent postoperative results.

Bucy, Bailey and I sat down after the operation and discussed what had happened. The brain is insensitive; the water might have caused a bit of local swelling if we had persisted in bathing the brain with it but only if we had removed a fine layer of covering tissue, the pia. Inadvertently, we had discovered that the inside lining of the brain is sensitive. So often in science discoveries are made serendipitously, by chance. Actually, I have always felt that the real purpose of an experimental laboratory is not so much to "test conjectures or hypotheses" but to furnish the opportunity to make unexpected and unintended observations.




*48.*

Bailey recalled that he had recently seen a patient who had been shot in the head. The bullet was lodged in one of his ventricles ("little stomachs") filled with cerebrospinal fluid. The patient's complaint: Sometimes he would wake in the morning in a foul mood. At other times he would awaken cheerful. He had learned that he could change his mood by positioning his head: If when he first arose, he hung his head face down over the side of the bed, he would become cheerful in a few minutes; when he tilted his head back, his black mood would return. Sure enough, X rays showed that by tilting his head forward or backward, the patient could change the location of the bullet, which would "drift" inside the ventricle.

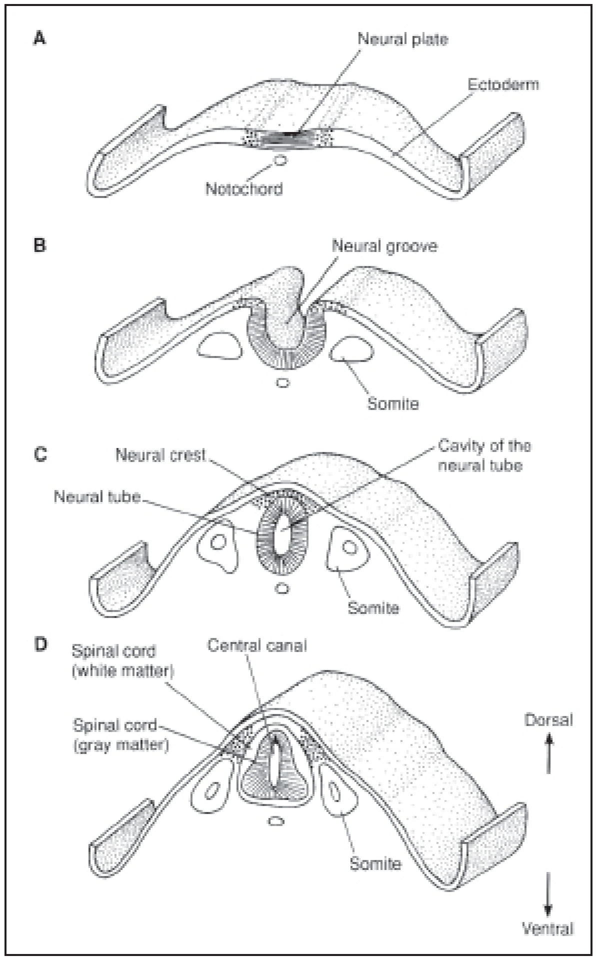
The question was whether or not to try to remove the bullet. The answer was no, because the surgery would require cutting into the ventricle to get the bullet out. Even minute temporary bleeding into the ventricle is extremely dangerous, usually followed by a long period of unconsciousness and often death. Bleeding elsewhere in the brain, once stopped, causes little if any injury. The brain tissue repairs itself much as would such an injury in the skin.

Bailey remarked that the symptoms shown by these two patients indicated that our ventricles, which are lined with stem cells with their undifferentiated membranes, could well be sensitive. The nervous system of the embryo develops from the same layer of cells as does our skin, the surface part of the layer folding in to become the innermost layer of a tube. It should not, therefore, have surprised us that this innermost part of the brain might have sensitivities similar to those of the skin.

With the patient's permission, we tested this idea in a subsequent surgical procedure in which one of the ventricles of the brain lay open and therefore did not have to be surgically entered. When we put slight local pressure on the exposed ventricle, the patient felt it as an ache in the back of his head; when we squirted small amounts of liquid, a little warmer or colder than the normal body temperature, onto the lining of the ventricle, the patient also experienced a headache. (Pressure and temperature are the two basic sensitivities of our skin.) We then proceeded with the intended surgical procedure, cutting the pain tract in the brain stem—a cut that the patient momentarily experienced as a sharp pain in the side of his head—with excellent postoperative results. (Actually the patient's head jumped up when he experienced the pain, a jump that fortunately made Bucy cut in just the right place. But we decided that next time the actual cut would be done under general anesthesia.)

Percival Bailey had classified brain tumors on the basis of their development from this innermost layer of cells lining the ventricles, the "ependyma," stem cells that have the potential of forming all sorts of tissue. Bailey had spent a whole year with me and another resident, peering down a microscope that was outfitted with side-extension tubes so we could simultaneously see what he was seeing. He would tell us fascinating stories about his work in Spain studying with Hortega del Rio and how Ramón y Cajal, Hortega's chief, was annoyed with Hortega for studying stem cells instead of nerve cells. In Chapter 2 of my 1971 book *Languages of the Brain*, and in Chapter 9 of this book, I summarized what

I had learned—bringing to bear what Bailey had taught us on how our brain can be modified to store experiences as memories.

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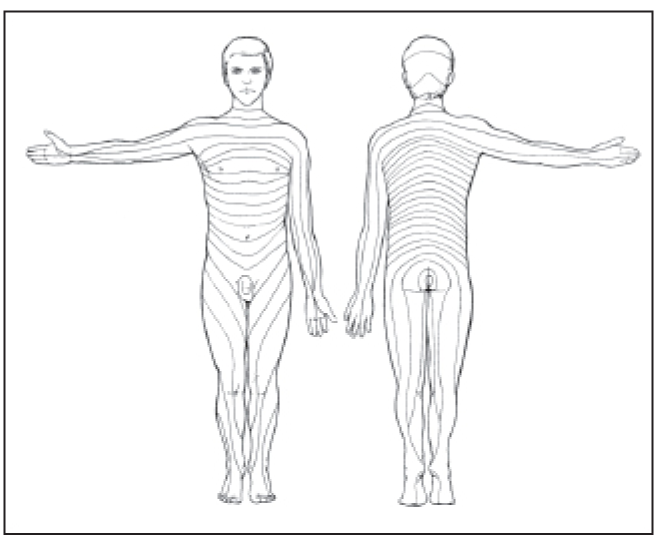
# The Core-Brain

At this juncture, a brief exploration of functional brain anatomy will help. The names of the divisions of the nervous system were established over the years prior to World War II. During these years, the nervous system was studied by dividing it horizontally, as one might study a skyscraper according to the floor where the inhabitants work. The resulting scheme carried forward the basic segmental "earthworm" plan of the rest of the body (in many instances, in my opinion, inappropriately as the cranial nerves are not organized according to the segmental pattern of the rest of the body).

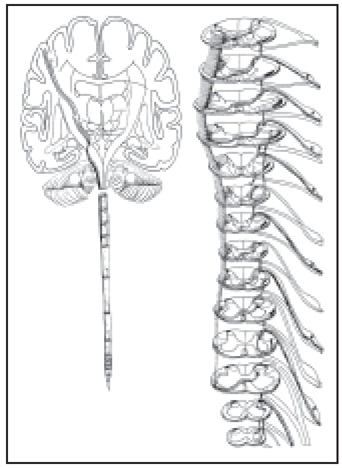
The tube we call the spinal cord enters our skull through the foramen magnum (Latin for the “big hole.”) Within the skull, the brain stem becomes the hindbrain. As we move forward, the hindbrain becomes the midbrain. Still further forward (which is “up” in upright humans) is the forebrain. The forebrain has a part called the thalamus (Latin for “chamber”), which is the way station of the spinal cord tracts to the brain cortex (Latin, “bark,” as on trees.) The most forward part of the brain stem is made up of the basal ganglia. During the development of the embryo, cells from the basal ganglia migrate away from the brainstem to form the brain cortex.

## A New View of the Brain

After World War II, techniques became available to study the nervous system from inside out. Most skyscrapers have a core that carries pipes for water and heat, a set of elevators, and an outer shell where people work. At UCLA Horace (Tid) Magoun and Don Lindsley studied the midbrain by electrically destroying its core. In Montreal, Wilder Penfield and Herbert Jasper studied the core of the thalamus by electrically stimulating it. Concurrently, at Yale, in John Fulton’s laboratory, using neurosurgical techniques, I was able to reach the inner aspects of the cortex, exploring them by electrical and chemical stimulation, and by making surgical removals.



*50. The segmental pattern of the human body*

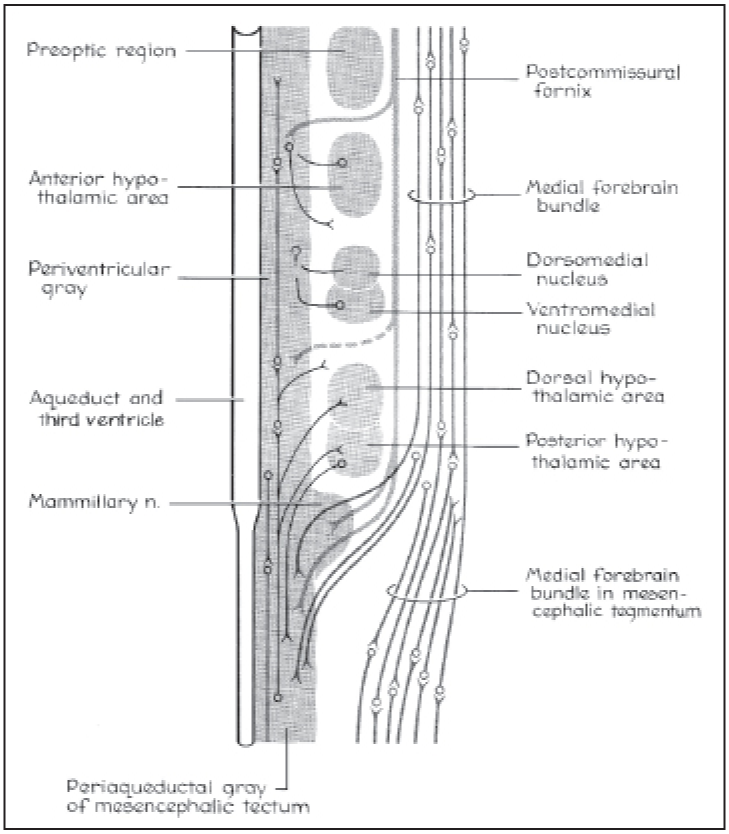


*51. The segmental pattern of the spinal cord and peripheral nerves*

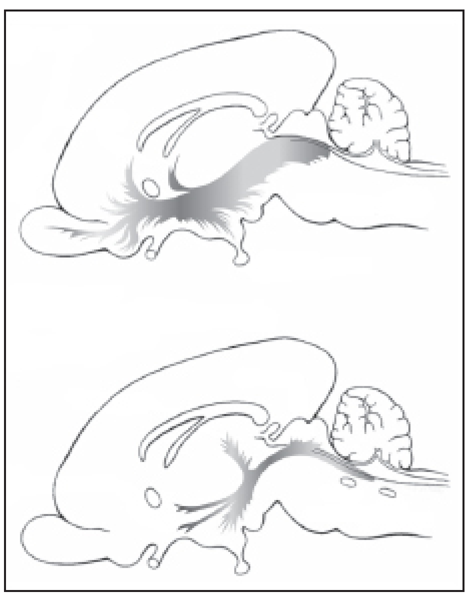
These new methods, pursued on three fronts, produced new insights into what we came to call the core-brain. From the midbrain forward there is actually a continuous band of cells that had earlier been divided into separate structures. In the midbrain, the gray matter (brain cells) around the central canal connecting the ventricles, is called the "periaqueductal gray" because, at that point, the canal inside the brain stem forms an aqueduct that leads from the brain stem ventricles (that we found to be so sensitive) to the ventricles of the forebrain (where the bullet had lodged in Bailey's patient.) Shortly, we'll see how important this gray matter is to our understanding of the way we process pain. The periaqueductal gray extends seamlessly forward into the hypothalamic region (which is the under part of the thalamus, its upper part being called the dorsal thalamus.) The gray matter of the hypothalamic region, in turn, seamlessly extends forward into the septal region where the brain's thermostat is housed.

The sensors that control the variety of behaviors that regulate metabolism are located in this band of cells bordering the ventricles. The gray matter that makes up the band regulates and makes possible the modification of a variety of behaviors such as drinking, eating, motor and sexual activity.

Control is homeostatic; that is, the behavior is turned on and turned off according to the sensitivity of the sensors. This sensitivity is set genetically but can be modified to some extent by our experience.




52. *(From* Brain and Perception*, 1991)*



*53. The median forebrain bundle (afferent and efferent) highlighting the concentric pattern of the brain. 52. (From* Brain and Perception*, 1991)*

The thermostats that control the temperature of our buildings work in this fashion. A sensor in the thermostat usually consists of two adjacent metal strips or wires that expand and touch, closing an electrical circuit as the room temperature increases. When the temperature in the room drops, the metal shrinks, opening the electrical circuit. Opening and closing the circuit can turn on an air-conditioning unit or a furnace. The homeostats in the core-brain turn on, and turn off, behaviors such as drinking and eating, which are controlled by their respective sensors. Roughly, drinking is controlled by the amount of salt in the blood and eating is controlled by the amount of sugar in the blood. More on these topics shortly.

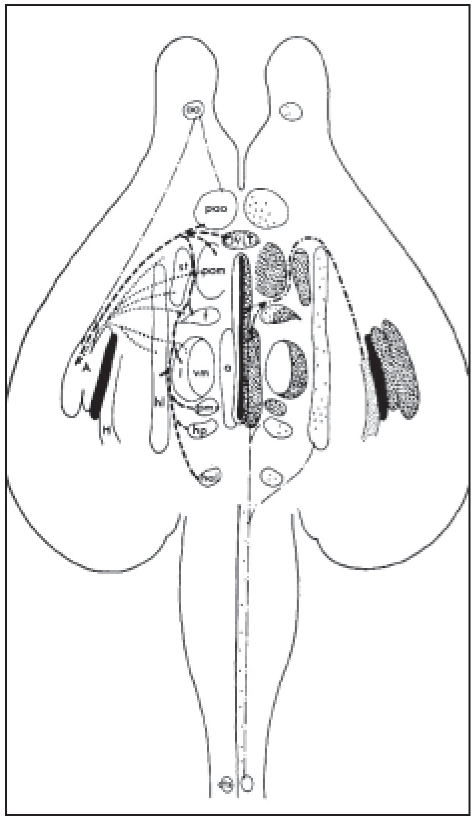
Ordinarily the loci of control over these behaviors are attributed to processing "centers." There is separation between these loci of control, but within the controlling region there is considerable distribution of function. Here are some examples:

The cells located around the central canal in the hindbrain control breathing, heart rate and blood pressure. When I arrived at Yale one of the graduate students wanted to know whether the "respiratory center" on one side of the hindbrain controlled breathing on the same side or the opposite side of the body. Under general anesthesia, he made a cut into the "respiratory center" of a rat's brain, but nothing happened to the animal's breathing. Perhaps the cut was inadequate. A week later he made another cut; deeper. Again nothing happened. After a week, yet another cut, and still no change in breathing. He then tried cutting into the breathing "center " on the other side of the brain stem. By this time he was surprised that the animal had survived so much surgery; his cuts led a zigzag path through the length of the hind-brain. Conclusion: control over breathing is distributed over a region among cells that do not form a "center."

By using a variety of chemical tagging and electrical stimulation techniques, brain scientists have found that such distribution of function is characteristic of the entire band of gray matter surrounding the ventricles. In the hypothalamic region of rats, stimulation of one point would result in wiggling of its tongue. Stimulation of an adjacent point led to swallowing, the next adjacent point to penile erection, and the next to swallowing again. The cells in the hypothalamic region that regulate the amount we eat are strung out almost to the midbrain, and those that are involved in regulating our basal temperature extend forward into the septal region. To talk of "centers" in the brain within which all cells are engaged in the same process is therefore misleading. Always there are patches of cells and their branches that are primarily devoted to one function intermingled to some extent with those devoted to another function. Thus, there are systems devoted to vision within which there are cells that are tuned to parts of the auditory spectrum. With respect to the regulation of internal body functions, processes such as chewing and swallowing often intermingle with cells that regulate ovulation and erections. Such an arrangement has the virtue of providing flexibility when new coalitions among functions are called for.

## Odd Bedfellows

We return now to the sensitivities shared by the tissue of the spinal canal and ventricles with those of the skin. The sensitivities of the skin can be classified into two sorts: touch and pressure make up one category, while pain and temperature make up the other. These two categories of sensitivities are clearly separated in our spinal cord. The nerves that convey the sensations of touch and pressure run up to our brain through the back part of the cord; those that convey pain and temperature run through the side of the cord. This arrangement allows surgeons to cut into the side of the cord in those patients who are experiencing intractable pain, in order to sever the patients' "pain and temperature" fibers without disturbing their sensation of touch. There is no way to isolate pain from temperature fibers, however. Thus, cutting into the spinal cord and severing the pain/ temperature nerves eliminates both pain and temperature sensibility. As noted above, the human body, its vertebrae and nervous system, is formed in segments, like those of an earthworm, thus sensibility is lost only in the segments below the cut but not above it. This segmentation becomes manifest when shingles develop: the itch and pain are usually restricted to one body segment.



*54. Example of core-brain receptor sites in rat brain: striped areas indicate uptake of labelled estrogen (female sex hormone) molecules. Lateral structure showing uptake is amygdala. (From Stumpf, 1970)*

Pain and temperature—what odd bedfellows! The story of how I came to understand how these fellows became bedded together follows in the remainder of this chapter. To begin, brain scientists were puzzled for a long time as to *how* we sense pain—because we possess *no* receptors that are specific to sensing pain. For touch, pressure, cold and hot there are specialized nerve endings that act as receptors—but even for these sensations the specialized receptors are unnecessary: we can feel these categories of sensation in parts of the body where such specialized receptors are absent. John Paul Nafe, an eminent professor of physiology working at Florida State University during the mid-20th century, suggested, on good evidence, that the nerve endings in the skin could be stimulated in two ways: the first is produced by depressing the skin, hence stretching the skin's nerve net laterally, which gives rise to the sense of touch or pressure, depending on the magnitude of the stretch. A second gradient from depth to surface—established by contraction and dilation of the skin's blood vessels—provides the input for sensing temperature. Nafe proposed that when the depth-to-surface gradient is activated from outward to inward, as when radiation comes from a heat source such as the sun, we feel warm; conversely, as we radiate out to our environment, activating the gradient from inward to outward, we feel cool.

But at extremes the distinction between sensing pain and sensing temperature disappears: with exposure to extreme hot or cold environmental situations, feelings of pain and even pleasure merge.

For example: I had an experience shared by many Arctic and Antarctic explorers. I was trekking with my companion to my cottage in deep drifts of snow, having had to park my car about a mile away from home. I get asthma in cold weather, and I was wheezing away. I soon felt tired and decided to rest for a moment, so I lay down in the snow. What a relief! I soon felt nice and warm and cozy despite an external temperature well below zero, and would have dropped off to sleep if my companion had not noticed that I had stopped. She kicked me and got me up and going.

At the extremes, our experience of warmth and cold become indistinguishable. Possibly this effect is related to the control of pain by our endorphins (endogenous morphine-like substances), the same chemicals that account for "second wind" during extended exertion. I'll have more to say on this topic shortly.

## The Search for "Pain in the Brain"

Where, within the brain, do the spinal cord nerve tracts that transmit our sensations of pain and temperature end up? One tract ends in the parietal lobe of the brain, the same place where the nerves that transmit our sensations of touch and pressure end up. Knowing this, in a few cases surgeons removed the cortex of the parietal lobes in an attempt to rid patients of intractable pain. This failed to work. On the other hand, when the most forward parts of the frontal lobes were removed or cut into, as in the lobotomy procedure, the intrusive *persistence* of a patient's pain, the suffering, always disappeared.

During the late 1940s, I came to the conclusion that persistent sensations of pain/temperature must reach the frontal lobes by way of a tract separate from the one that reached the parietal lobe. I therefore undertook a series of studies (the last of which was published in 1976) to discover, not only the pathways by which pain sensations reached the frontal cortex of our brain, but *how* that cortex controlled our experience of pain. An immediate difficulty to be faced was the fact that I did not use painful stimulation in my animal experiments. I resolved this by assuming that, if I studied temperature, pain's odd bedfellow, I would be a long way toward unlocking the secret of frontal lobe control of pain.

Pain is not a single sensation, even at the skin. There is "fast" pain and "slow" pain. Fast pain is discrete as when we feel a pinprick. We can tell where we were pricked and when the prick occurred. By contrast, slow pain is hard to locate in either place or time. It takes us longer to feel the slow pain, thus the name "slow." The difference between fast and slow pain is due to a difference in the size of the nerve fibers that transmit the sensation from the skin to the spinal cord. The nerve fibers that transmit fast pain are large; the nerve fibers that transmit slow pain are very small. Interestingly, the small nerve fibers also mediate temperature sensations, fibers that become even more intertwined with pain fibers in the spinal cord.

The difference between the two types of pain is classically demonstrated in patients who have a form of syphilis called tabes dorsalis, which can become manifest long after the initial infection. These patients have lost their fast pain but retained their slow pain because their large nerve fibers have been damaged where they enter the spinal cord.

The distinction between fast and slow pain is maintained in the brain stem and the brain: the fast pain tracts end in the parietal lobe of the brain, which left unsettled the issue as to whether slow pain reaches the frontal lobe. A clue as to where these slow pain-related systems might be located is that in the brain stem, surrounding the connection between the ventricles, lies a system (the periaqueductal gray) that is sensitive to morphine-like substances, the endorphins, which suppress the experience of pain.

My research therefore had to concentrate on finding evidence that forebrain systems might be involved in the experiencing of pain—and to use the relation between pain and temperature as the tool for such a search.

I initially trained monkeys that had been used in a variety of other studies to home in on the parts of the brain that might be involved in sensing temperature. I taught the monkeys to choose the colder of two test tubes to receive a peanut. I placed the test tubes either in buckets of ice or of hot water, randomly varying the cold and the hot between trials. I found that monkeys with damage to the bottom of the frontal lobe and the medial surface of the temporal lobe were impaired in making the choice. However, the failure to choose was not equally severe in all the monkeys and making the choice took a variable period of time.

With the help of a postdoctoral student and others with technical expertise in the laboratory—in the acknowledgments in the publication we noted that since the experiment had taken over five years to complete, the whole laboratory had had a hand in its execution at one time or another—we set out to repeat my earlier experiments with better control over our stimuli: a metal plate was cooled or heated between trials in a random order. The monkeys were trained to press one or the other of two panels: one if the plate felt cold, the other if the plate felt warm. As a control, an identical visual task was set up in which the monkeys were shown a "+" or a "#" and had to press one panel when they saw a + and the other panel when they saw the #. We then placed electrodes on the surface of the parietal lobe and on the bottom of the frontal cortex and the medial part of the temporal lobe—the areas that had given promise of being involved in the earlier study.

The experiment gave excellent results: when we disrupted brain function by stimulating the frontal and temporal cortex and the relevant pathways to these parts of the brain, the monkeys completely failed to make the temperature choice but performed perfectly on the visual one.

They again performed well on the temperature choice when the stimulation was turned off. Nor did stimulation of the parietal lobe have an effect on the performance of the monkeys, a result that supported the findings of other studies that had shown that only very *fine differences* in temperature—not gross differences as used in our study were affected by surgical resection of the parietal cortex of monkeys. We concluded that perhaps slow pain, as indicated by its odd bedfellow temperature, reached the frontal cortex and not the parietal cortex of the brain.

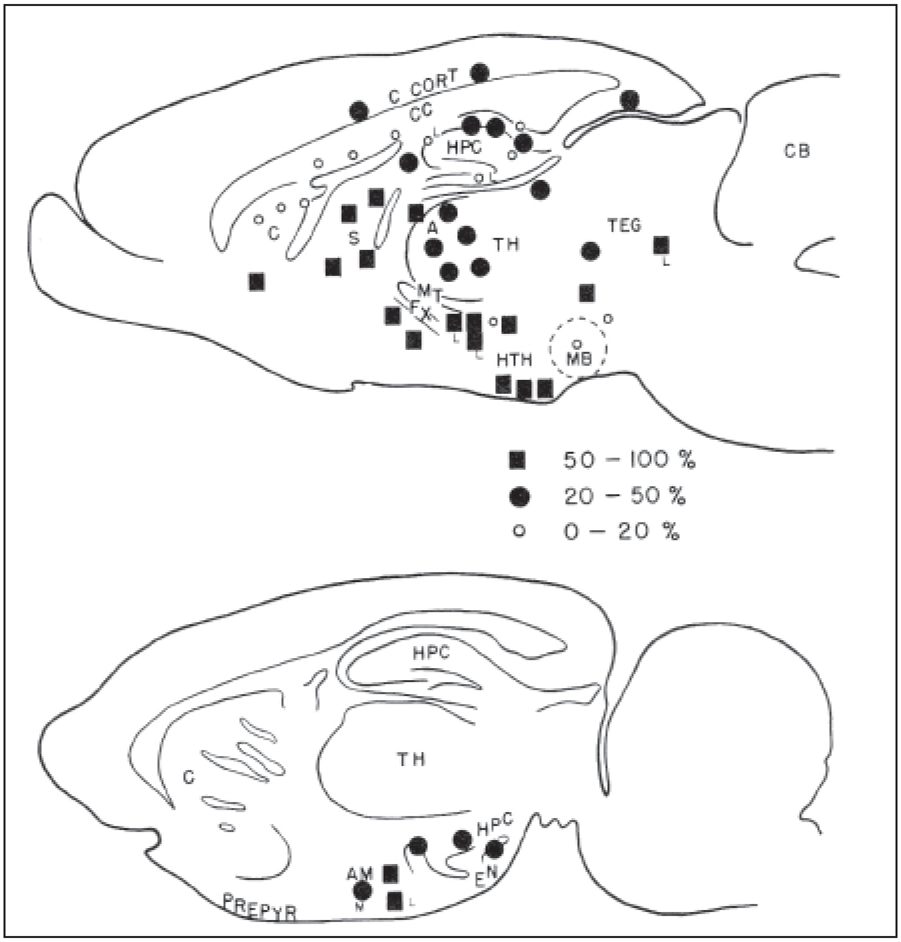
While I was attaining some insight into the brain systems entailed in controlling the persistence of intractable "slow pain"—the pain that is alleviated by frontal lobe surgery—postdoctoral fellows in Don Hebb's department at McGill University were discovering what constitutes the essential brain process involved in our experience of pleasure.

## Pleasure: Self-Stimulating the Brain

In the 1950s, Peter Milner and James Olds, working in Don Hebb's laboratory at McGill in Montreal, Canada, stumbled on an exciting experimental result. They wanted to study whether they could influence the rate of learning by electrical stimulation of a part of the brain stem. The rat was to learn to push a hinged platform placed on the floor of its cage whenever the brain stimulus was turned on. Within a few minutes the experimenters were surprised to see that the rat was pushing the platform without the experimenters turning on the electrical stimulation to its brain. A short circuit had occurred that hooked up pushing the platform with the electrical stimulation. As Milner and Olds were searching for the short circuit, they noticed that the rat was pushing the platform more and more often. Serendipitously, they had discovered that the rat would push a platform *in order to electrically stimulate its brain*. The brain stimulation was "rewarding," and perhaps felt "pleasurable," to the animal.

When Milner and Olds looked at the brain of the rat to see where they had implanted their electrode, they found that it was much farther forward than they had planned. Instead of being in the brain stem, the electrode had been placed in a tract that courses along the sides of the centrally placed ventricle of the brain. A few more experiments showed this tract and the surrounding tissue to be the locations from which electrical self-stimulation of the brain could be obtained.

Some months after Milner and Olds made their discovery, Jim Olds, his wife, and I were having lunch together in Montreal. I took the opportunity to suggest that it would be important to map all of the brain sites from where self-stimulation of the brain could be obtained. I was eager to know whether these sites might include sites in the olfactory (by now called the limbic) system of the brain. Jim, who had obtained his degree in sociology from Harvard and was delving into brain science for the first time, said that he was not up to such a tedious task. His wife Nicki, however, shared my view that the mapping would be important. She had a doctorate in philosophy and in the history of science and she was eager to get into the laboratory. With Jim's and my encouragement, she volunteered to do the experiments.



*55. Places in a rat's brain where self-stimulation is elicited. (From* Brain and Perception*, 1991)*

The results of her mapping showed that sites of self-stimulation were located not only in the tract adjacent to the core ventricle gray matter but also in what is the rat's olfactory brain. Further, the amount of effort the rat would expend (how fast and for how long the rat would push the panel) on self-stimulating was a function of the three systems that I had recently outlined in a 1954 paper, "Functions of the 'Olfactory' Brain."

The discovery of self-stimulation by Olds and Milner was celebrated as locating the "pleasure centers" in the brain. When a psychiatrist in New Orleans electrically stimulated these brain sites in humans, the patient stated that he or she was experiencing a pleasant feeling. One patient repeatedly professed deep love for the psychiatrist who had turned on the stimulus—but the feeling was present only during the stimulation!

By this time I had arrived at Yale, in John Fulton's Department of Physiology, where another set of experiments was under way in which an experimenter turned on —and left on—an electrical stimulus in the same brain locations as in the Olds and Milner experiments. The rats would turn *off* this ongoing electrical stimulus by pushing a panel, but the electrical stimulation would turn itself *on* again after a brief pause. In this experiment, the rat would dutifully keep turning *off* the stimulation. This was the mirror image of the *turn-on* self-stimulation effect. The location of these turn-off effects was the same as those that produced the turn-on effect.

I suggested to our graduate student who was doing the experiment that the stimulation be adjusted so that, in the turn-on experiment, the stimulus stays on after being turned on, to see if the rat would turn it off. It did. And when the electrical stimulation remained off, the rat turned it on again. Jokingly we called the graduate student's thesis "Sex in the Brain!"

On the basis of this result, we can interpret the self-stimulation experiments as "biasing," that is, modifying the context within which the naturally occurring pleasure is processed. Nicki Olds showed that this is an excellent explanation as she explored the interaction between self-stimulation with food and water intake and sexual behavior. She showed that "pleasure" is ordinarily self-limiting, although, under certain conditions, it can become "addictive." Jim Olds pointed out that the danger of potential addiction is why there are so many social taboos that aim to constrain the pursuit of pleasure. (I'll have more to say about the conditions that lead to addiction in Chapter 19.)

Ordinarily, pleasure has an appetitive phase that ends in satiety. The finding of how the brain process works to produce an appetitive and a satiety phase has important clinical implications. Pleasure is self-limiting unless you trick the process, as in bulimia, by short-circuiting it: the bulimic person artificially empties his stomach so that the signals that usually signify satiety, such as a full stomach and absorption of fats, are disrupted. Is the bulimic's short-circuiting process a parallel to that which occurs in self-stimulation of the brain? Or, as in anorexia, can culture play the role of "keeping the stimulation on" in the role of a person's self image so that the person's brain is always set to experience only a "turn-off" mode. We need to find noninvasive ways by which we can change the settings in the brains of the persons with these eating disorders.

Evidence that further associates pleasure with pain came from experiments that showed pain to be a process in which the experience of pleasure can be the antecedent of the experience of pain. The experimental findings that led to this conclusion are taken up shortly.

To summarize what we have covered so far in this chapter: Our world within is formed by stimulation of a variety of sensors lining, and adjacent to, the central canal of the nervous system, a canal in which the cerebrospinal fluid circulates. *In warm-blooded animals, including humans, the sensors are linked to one another through the regulation of behaviors such as drinking, eating and motor activity that regulate our basal temperature: thus the explanation for the odd pairing of pain and temperature in our spinal cord and brain is that the regulation of temperature is the basis of "how" we come to experience pleasure*.

The following are examples of what to me were exciting discoveries of the sensitivities and their regulation of pleasure and pain by these "core-brain" sensors.

## Brain and the Regulation of Thirst

I remember that while I was in college, I asked my father what makes us thirsty, other than dryness of the mouth and tongue? How do we know immediately just how much to drink, how many swallows to take to replenish our thirst—for instance, after a tennis match?

The discovery of how the brain regulates thirst is one of those delightful sagas that occasionally intrude among the more disciplined scientific enterprises. There is a disorder known as diabetes insipidus during which the person urinates huge amounts—and, as a consequence, is continually thirsty. This disorder is caused by an imbalance in the secretion of a pituitary hormone. The question arises: What ordinarily controls the secretion of this hormone?

In the late 1880s, my father had done his medical school thesis on the control of the pituitary gland by cells in the hypothalamic region. When I first found this out, I was surprised that the hypothalamic control over the pituitary secretions was already known. But the specific manner of how this control operated was not known even in the mid-1940s. After World War II, Pier Anderson and his colleagues at the Technical University of Stockholm in Sweden devised a simple experiment that revealed the "how" of the hypothalamic control of the pituitary gland in the production of thirst. Using a goat, they placed a small tube into the ventricle just above the pituitary gland. In this location, a network of blood vessels connects the hypothalamic region with the pituitary gland. Anderson took a pinch of table salt and poured it down the tube. The goat rushed to a nearby fountain and drank and drank and drank and would have burst its belly had not Anderson been prepared to put another tube into its stomach. Further research showed that the amount of drinking was directly proportional to the concentration of salt in the ventricle.

I had to see this for myself, so on a visit to Stockholm I made an appointment with Anderson. There was the fountain in the center of a square surrounded by stables. I made friends with one of the goats who had a tube in his tummy. A minute amount of salt was inserted into another small tube in the goat's head. The goat and I trotted off together to the fountain and the goat drank and drank, with the water pouring out of the tube in his stomach. Many carefully done experiments showed the "how" of the thirst process and how the exact quantity of water drunk is determined by the proportion of salt in the sensors lining the ventricle surrounding the tissue above the pituitary. Here was a simple demonstration of the sensitivity and the power of control that the core-brain sensors exert over our behavior—and, I believe, over our feelings, if my reading of the goat's urgency in getting to the fountain is correct.

## Masochism: A "Thirst" for Pain

Another major event in my understanding of brain function came with the discovery of the endorphins. Surprise: *pain turned out to be processed in much the same way as pleasure*. As I previously noted, we have no specific receptors for pain. But pain can be produced by excessive stimulation, of whatever sort, even by a very bright light or by an overly loud sound. This is true also of excessive stimulation of the tracts in our spinal cord and brain stem that relay signals from our body and face. Pain is coordinate with excessive stimulation when it overwhelms our ordinarily ordered sensory processes.

No one has found a "center" for pain in the brain. However, during the 1970s, experiments with rats showed that when the cells of the periaqueductal gray matter are electrically stimulated, pain produced by a peripheral stimulus, such as pinching the skin, is turned off. At about the same time, several laboratories reported that morphine acts selectively on the sensors in the aqueduct adjacent to the periaqueductal gray. Next, experimenters showed that a hormone called endorphin, whose effects were almost identical to those of morphine, is secreted by our pituitary gland and that the amount of secretion is sensed and regulated by cells in the hypothalamic region and in the periaqueductal gray. These endorphins account for protection against the pain produced by pinching the skin, as in the experiments during electrical stimulation of the periaqueductal gray.

Further research demonstrated that the stimulation and the endorphins influenced the part of the spinal cord where sensory input from the pinching becomes organized. The theory, and its confirmation that predicted this result, is known as the "gating theory," popularized by Patrick Wall, professor at MIT and later at the University of London, and by Ronald Melzack, professor at McGill University in Montreal. The theory states that *our ordinary sensations are patterned and that, when excessive stimulation overrides the patterned sensory input, pain is experienced*.

The results of this research demonstrate that pain is controlled homeostatically, exactly as thirst, hunger and temperature are controlled! (In fact, excitations of the brain that result in the secretion of endorphins also produce goose bumps and the sensations of chills and thrills.) When we are tired, our endorphins are low and small injuries can seem to hurt a lot. When we get our second wind during running, our endorphins kick in. During the 1960s and 70s, I told my students that it is stupid to buy drugs on the street when you can generate your own homemade supply by exercising.

An incident highlights the novelty of these discoveries about endorphins and the homeostatic regulation of pain. Science can provide answers to puzzles that often stump philosophers. This may hardly seem to be news to most of us—but needs to be mentioned because a number of philosophers and even some scientists have stated that the mind/matter relationship is one that only philosophers can resolve—that no matter how many experiments we do, such experiments, or the theories we base on them, will be irrelevant to the issue of the relationship between mind and brain. On one occasion, after my colleague Sir John Eccles had given a splendid talk, a noted philosopher got up and made remarks to this effect. Eccles and I were both furious. It was lunchtime, and Eccles took me by the hand as we marched out and said, “Karl, we simply must do our own philosophy.” Which we then did.

Shortly after the discovery of endorphins, I attended a meeting on the topic of philosophy in medicine at the medical school of the University of Connecticut. One philosopher delivered a very long paper in which he pointed out how unsolvable the topic of pain is: “If one defines pain behaviorally, in terms of escape or avoidance, what about masochism?” For over an hour he harped on that same theme over and over. I was the discussant of the paper and based my critique on the recent discoveries of the endorphins: One of my students had just completed a study involving sado-masochism, demonstrating that, at least in her sample groups, there was never any real pain experienced. Rather the experience was an almost-pain, more like an itch. The participants in her groups were so well attuned to one another that they never went beyond that threshold to a stimulation that produced actual pain. True, this is not the stereotype one gets from some of the stories written by the Marquis de Sade. However, other, more contemporary tales, as for instance *Story of O*, do resemble the careful analysis that my student came up with.

When I start to scratch a mosquito bite, histamine has already been secreted at my local nerve endings at the site of the bite. The histamine affects the local small blood vessels to produce an itch, almost like a slight burning sensation. I scratch until it hurts, then I stop scratching. I’m thirsty: I drink until I feel full. I eat until I feel sated. The parallel between the appetitive-consummatory cycle in homeostatically controlled experiences and those operating in our experiencing of pain is evident. Scientific experiment, leavened by philosophical reasoning, provided an answer that philosophy alone could never have attained.

The world within is governed by homeostatic patterns. These patterns are not static but change with circumstance; thus, Waddington coined the term “homeorhetic,” which has found favor. Whether homeo-static or homeorhetic, the essence of the patterns is a regular recurrence of an appetitive-satiety, a “go” and “stop,” cycle. Both pleasure and pain partake of this pattern.

Much excitement, which I shared, was generated during the 1950s as these insights about homeostasis and homeorhesis were gained. As I described in Chapter 5, the principles that were initially formed with regard to the world within were shown to be equally valid for sensory processing. All senses were shown to be controlled by feedback from the brain—with the exception of primate vision, which I set my laboratory to discover over the next decades. As noted earlier, a result of our excitement was that George Miller, Eugene Galanter and I wrote a book published in 1960, *Plans and the Structure of Behavior,* which related our insights to experimental psychology and to how computer programs are organized.

Go- and stop-homeorhetic cycles are regulated by higher-order modulations, anticipated in *Plans* and the topic of the next chapter.

## In Summary

1. The brain is lined with a layer of stem cells that is sensitive to the same stimuli as is the skin from which they are derived in the embryo: pressure and temperature—and, in addition, to changes in the salinity of the cerebrospinal fluid bathing them.
2. Surrounding the stem-cell layer are control systems of brain cells that, when electrically excited, turn on and turn off behavior. These systems have been interpreted to provide comfort (pleasure) and discomfort (pain) to the organism so stimulated, and this interpretation has been confirmed by verbal reports from humans stimulated in this fashion.
3. A stimulus is felt as painful when any pattern of stimulation is overwhelming and disorganized.
4. Endogenous chemicals, endorphins, act as protectors against pain. When activated, these chemicals produce thrills and chills.
5. A stimulus is felt as pleasurable when (in warm-blooded animals) it activates the metabolic processes anchored in the regulation of temperature. Finding temperature regulation to be the root of pleasure accounts for the previously un- understood intimate intermingling of the pain and temperature tracts in the spinal cord.

# Chapter 10
## The Frontolimbic Forebrain: Initial Forays

Wherein I describe my initial discoveries that defined the limbic systems of the brain and the relation of the prefrontal cortex to those systems.

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*Some strange commotion*
*Is in his brain: he bites his lip and starts:*
*Stops on a sudden, looks upon the ground,*
*Then lays his finger on his temple; straight,*
*Springs out into fast gait; then, stops again,*
*Strikes his breast hard; and anon, he casts*
*His eye against the moon: in most strange postures*
*We have seen him set himself.*

—*Henry VIII,* Act III, Scene 2.
Quoted by Charles Darwin*, The Expression of the Emotions in Man and Animals,* 1872

# The Yale Years

1948 was a critical year for me. I took and passed the exams that certified me as a member of the American Board of Neurological Surgery and was appointed assistant professor in the Departments of Physiology and Psychology at Yale University. I thus achieved my long-sought entrance into Academe through the offices of John Fulton, the head of the Department of Physiology.

My relationship with Fulton began during the late 1930s while I was a student at the University of Chicago. The first edition of Fulton's classic text on the *Physiology of the Nervous System* was published and made available the weekend before my final exam in a course in physiology given by Ralph Gerard. I was mesmerized by Fulton's text: it laid out what was then known, so clearly and thoroughly, that I could not put the book down. On Monday, Gerard posed a single question for the final: "Discuss the organization of the nervous system." I filled blue book after blue book, basing my answer on Fulton's text, until the time allotted was up. Gerard told me that it was the best answer he had ever received on any examination. Fortunately, he had not yet seen the Fulton text.

My next encounter with Fulton was in 1943, while I was an intern-resident in neurosurgery with Paul Bucy. We often discussed the scientific aspects of the surgical operations we were engaged in, and Bucy told me that if I ever wanted to do research, Fulton's department at Yale would be the place to go.

Therefore, while in practice and working in Karl Lashley's laboratory in Jacksonville, Florida, I expressed my desire to get to Yale (which owned the laboratory). Lashley wrote letters of recommendation to the dean—and received no answer. (Lashley at the same time was trying to get Nico Tinbergen, who later received the Nobel Prize, placed at Harvard, with similar negative results.) And I was asking Bucy and Percival Bailey at the Illinois Institute of Neurology and Psychiatry to write letters of recommendation. Bailey's reply was succinct as was his wont: "Karl, if you are thinking of obtaining a job like mine, your chances are slim as I intend to hang onto the one I have." (He changed his mind a decade or so later when Warren McCulloch moved permanently to MIT, and I was offered his research position at the Illinois Institute. But by that time my laboratory was already well established at Stanford.)

In 1948, I took the opportunity to visit Fulton personally. Fred Mettler at Columbia University had invited me to New York to discuss his frontal lobe topectomy project. I had had a ward of patients assigned to me upon whom to perform frontal lobotomies. As a well-trained surgeon, I held to the edict: "*Primum non nocere*"—"First do no harm." I was administering behavioral tests to the patients, and they were improving, given the personal attention involved. (More on this in Chapter 16.) I was therefore interested in Mettler's project, and he was graciously inviting me to see what was going on.

I decided that while in New York I would visit Fulton in nearby New Haven and had made an appointment to meet him in the Yale Medical School Library. I drove up to Yale, approached the hallowed halls and felt like genuflecting as I entered the rotunda leading to the library. Fulton greeted me warmly, and we talked about his experiments with the chimpanzees Becky and Lucy upon whom he had performed frontal lobectomies. I told him of my results at the Yerkes Laboratory and that they did not corroborate his findings. He fetched two large volumes of protocols, gave them to me to read, and said he'd meet me for lunch.

What I found is described in detail in Chapter 16. It agreed with what I had found but totally disagreed with the interpretation that had been presented to the scientific community. I met Fulton for lunch. He asked if I had found what I wanted—my answer was yes—but he asked nothing about the particulars of what I had found. I remember little else of the meal after he next asked, "Would I like to come work with him?" !!!!

A few months later, I received a telegram stating that he had received the funding from the Veterans Administration he had been waiting for, and could I start in two weeks? I finished what I could and started at Yale the day before Fulton left for London. The rest has become, as they say, history.

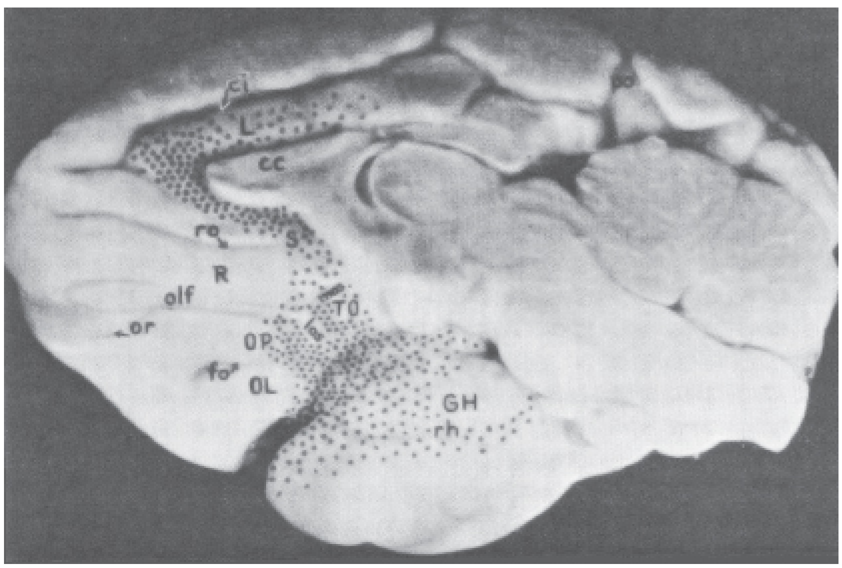
## Electrical and Chemical Stimulation of the Limbic Forebrain

In the previous chapter, I detailed the form that brain processes take in generating our feelings of pain and pleasure. Closely related are the brain processes that deal with the autonomic nervous system that regulates our visceral and endocrine functions. In this chapter, I describe my discoveries—while I was at Yale University in John Fulton's Department of Physiology—of the brain systems that deal with those visceral body functions and their presumed relationship to emotional and motivational behavior.

A persistent theme in describing how our body participates in the generation of emotions and motivations was formulated by William James. James suggested that when we perceive an emotionally exciting sensory event, the brain sends a message to our body, which responds to the stimulus by evoking different bodily (especially visceral) reactions. The emotion is due to our sensing these body reactions. His formulation is known as the "James-Lange theory." Lange had proposed that the body's blood vessels provide the signals that we interpret as an emotion. James suggested that not only blood vessels but also viscera, such as the gut and heart, generate these signals. Occasionally, James also mentions the muscles as originating such signals, and more recently Antonio Damasio, professor of neurology at the University of Southern California, in a 1994 book, *Descartes' Error*, called attention to the variety of signals arising in the body that contribute to our feelings. He calls these signals "somatic markers."

One of the reasons I was attracted to Fulton's laboratory at Yale was that the laboratory had built an electrical stimulation device with which brain stimulations could produce changes in blood pressure, heart and respiratory rate, and other visceral changes. I had tried unsuccessfully to produce such changes with an old alternating-current device called a "Harvard inductorium." Penfield told me that he had had some success in changing heart rate using the inductorium to stimulate the cortex on the upper, medial surface of the temporal lobe, but that he could not reproduce this result very often. The Yale apparatus put out "square-wave" pulses, and the duration of the pulses could be controlled. When that duration was adjusted to a millisecond, the visceral changes produced by cortical stimulation were invariably produced.

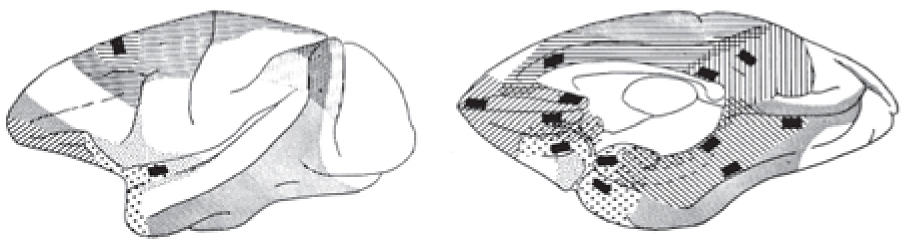
The studies accomplished at Yale using this square-wave stimulator had shown that visceral responses could be obtained by stimulations of the cingulate gyrus and the cortex at the base of the frontal lobe. I devised a method that exposed not only these areas of the cortex but that of the "insular" cortex buried in the lateral fissure between the frontal and temporal lobes and the adjacent cortex of the front end of the temporal lobe surrounding the amygdala as well. Using these techniques, assisted by a graduate student, Birger Kaada, and a postdoctoral neurosurgical student, Jerome Epstein, I was able to map a continuous region of cortex extending from the temporal lobe to the cingulate cortex. Electrical stimulation of this cortex produced changes in blood pressure, heart, and respiratory rate. We recorded these changes by means of a long needle hooked up to a rotating set of drums over which we stretched paper we had "smoked" using a smoking candle or gas burner. After obtaining a record, we shellacked the paper and waited until the next morning for it to dry. We called the region from which we obtained our responses the "mediobasal motor cortex" to distinguish it from the classical motor cortex on the lateral surface of our brain. Today, a more memorable name would be "the limbic motor cortex."




*56. The Limbic Motor Cortex*

I next turned to using chemical stimulation of the brain. During my residency in neurosurgery, I had assisted Percival Bailey, Warren McCulloch and Gerhard von Bonin at the Neuropsychiatric Institute of the University of Illinois at Chicago in their chemical stimulations of the monkey and chimpanzee brain, stimulations they called "strychnine neuronography." Neuronography outlined brain systems that were intimately interconnected, clearly separating these from the surrounding regions. But Bailey, McCulloch and von Bonin mapped only the lateral surface of the brain. Using my newly devised techniques to provide access to the medial aspects of the brain, I therefore went to work, assisted by Paul MacLean, who had joined my project in Fulton's department at Yale, to map these hitherto inaccessible regions of the brain.

Neuronography demonstrated the division of the limbic forebrain into the two systems: the amygdala system and the hippocampal system, each with intimate connections to a part of the frontal cortex. We were able to clearly demarcate limbic from non-limbic regions; but, as in my behavioral studies, the "limbic" cortex included neocortical additions in the primate, additions that were not present in the cat.



*57. This figure, depicting the lateral and inferomedial aspects of a monkey's brain shows diagrammatically the distribution of regions and segments referred to in the text. Dotted stippling denotes frontotemporal; rosroventral striations denote medial occipitotemporal; vertical striations denote medial parieto-occipital; horizontal straitions denote medial frontoparietal; dorsorostral straiations denote medial frontal.*

The other important result of our neuronographic studies was that, though there were major inputs to the hippocampus from the adjacent isocortex, there were no such outputs from the hippocampus to adjacent non-limbic cortex. The output from the hippocampus is to the amygdala and accumbens, and through the subcortical connections of the Papez circuit. MacLean, always adept at coining names for the results of our experiments, suggested that this one-directional flow of signals from isocortex to the limbic cortex indicated a "schizophysiology" in that the "limbic systems," though open to influence from the rest of the cortex, worked to some extent independently from the isocortex—much as James Papez had suggested. Papez was most pleased with our results when MacLean and I recounted them on a visit to his laboratory.

## Emotions and the Limbic Brain

How then are the limbic parts of the brain involved in organizing our emotions? My initial inquiries indicated that there was some considerable substance to the views formulated by William James and James Papez, but at the same time, I was at a loss when I tried to answer *how* these systems worked in organizing our emotions. An answer had to come from carefully analyzing the composition of what constitutes our emotions and motivations, and relating the constituents to particular brain systems. When I wrote my book *Brain and Perception*, I found that *I needed to consider the entire brain*, not just the sensory input systems, to determine how our brain organizes our perceptions.

The same situation applies in studying emotions. For instance, we can describe the changes in behavior following removal or electrical stimulation of the amygdala, but when we attach names to the emotions that accompany those changes in behavior we need to use the parts of the brain that are involved in producing names, parts of the brain considerably removed from the limbic systems. Thus, to attribute the taming of a monkey to a loss of "fear" may or may not be correct, as we will see in the next chapter. A realistic view of the relationship between emotion and motivation to the organization of brain systems, including those called limbic, can be attained only when all the facets of the behavioral and brain systems are considered.

## The Yale-Hartford Laboratories

In 1951, three years after Fulton asked me to come to Yale, he was asked to head the medical school's library, which he had founded and nourished, and to give up the Department of Physiology. Though I could continue to teach at Yale, most of the physiology department's laboratory space was now assigned to biochemistry. I therefore moved the bulk of my laboratory to a new research building at a nearby mental hospital, the Hartford Retreat, renamed the Institute of Living. I needed financial support to make the move.

David Rioch, psychiatrist and neuroscientist, as well as a dear friend, had just become director of the Army's Research Laboratories at the Walter Reed Hospital in Washington, DC, and was, at that time, bringing together a group of superb investigators to shed light on the complexities of the brain/emotion/motivation relationship. When we started we knew practically nothing about the limbic forebrain, certainly nothing about the relation of the prefrontal cortex to the limbic systems and what these parts of the brain might have to do with emotion and motivation. Rioch had worked on hypothalamic systems that, at the time, were considered the "head ganglion of the autonomic nervous system," which by definition excluded cortical contributions to visceral and emotional processing. It was my work with Bucy, supported by Fulton, that had overturned that earlier conception.

The immediate question Rioch was addressing was set by troops who could hardly make it to their battle station in the Korean war, but when, in an experimental setting, were told that orders had been changed and to reverse their course to go for R and R in Japan, would cheer and sing and march double time. What chemistry or brain processes accompanied such a change in emotion and motivation?

It was Rioch who funded my initial grant applications to pursue my research. I asked Rioch if the Army might provide some $2,000 for automated behavioral testing equipment. Rioch replied that this would be impossible. I must ask for at least $20,000 since it would cost $2,000 just to do the paper work in processing my grant application. I asked for, and received the $20,000. For almost a decade, this money, plus additional funding, supported a promising and productive group of graduate students, not only from Yale but also from Harvard, Stanford, the University of California at Berkeley, and McGill University in Canada. The laboratory at the Institute became a Mecca for students intensely interested in the relationship between brain and behavior.

## Functions of the Olfactory Brain

In 1952, with the help of my then Yale graduate student Larry Kruger, I published a paper titled "Functions of the Olfactory Brain." We did not, at the time, use the term "limbic systems" for this constellation of structures—that formulation was to be achieved shortly. I received over 2,000 reprint requests for that paper.

We were able to confirm the division of the "olfac-tory brain" (beyond the olfactory sensory structures per se) that had been attained with chemical neuronography into two distinct segments on the basis of the results of electrical stimulations: 1) those parts that receive a direct input from olfactory structures (which lie just behind the nose and receive an input from the receptors in the nose) and 2) a set of structures that receives input from the earlier segment. The first segment is composed of a system that centers on the amygdala, which has a cortical component; the second segment is composed of the circuit that includes the hippocampal and cingulate cortexes.

In our paper, Kruger and I noted that in primates, including humans, a band of new six-layered neo-cortex immediately surrounds the allocortex in the neighborhood of the amygdala and the cortical systems adjacent to it. In our classification we were following the lead of Filomonov, a Russian neuro-anatomist whom I visited in Moscow to learn firsthand why he had included these newer components in what he called "juxt-allocortex" (*juxt*, "next to"). Juxt-allocortex, more recently renamed "peri-allocortex" is new cortex, appearing for the first time in primates. As a result, the use of the name "neocortex" to distinguish its functions from those of the allocortex is inappropriate.

This detail is important because the popular idea that our brains are made up of old cortex that organizes more primitive behaviors such as emotions and motivations—as opposed to new cortex that serves cognitive functions— doesn't hold up. Thus, many of our social institutions that are based on this emotions-versus-cognitions dichotomy badly need revamping. I'll have much more to say about this in Chapter 17.

My behavioral, electrical and chemical stimulation experiments undertaken at Yale corroborated the anatomical considerations that had led to the inclusion of juxtallo-cortical formations as intimate parts of the allocortex adjacent to it.

The second segment of the olfactory brain was the hippocampal-cingulate system. This system had been singled out in the 1920s and 1930s by the eminent Viennese neurologist Constantin von Economo and by neuro-anato-mist James W. Papez in Columbus, Ohio, as generating our emotional feelings and their expression. Their reasoning was based purely on anatomical connections: Fibers from the *hippocampus* connect to the *septal and hypothalamic region*, which in turn connects to the *thalamus*, whose fibers reach the *cingulate* cortex which then connects back into the *hippocampus*. This circuit is now named after Papez. The Papez circuit was thought to be involved in emotions because our emotions often seem to go round and round like a self- sustaining circuit. The behavioral idea is a good one: during the 1970s, I used to give lectures on "The Hang-up Theory of Emotions"—that emotions are like getting stuck in a loop. But providing evidence for the anatomy-based belief that the Papez circuit is involved in generating emotions has proved to be considerably more elusive.

My research on monkeys, which I had started at the Yerkes Laboratory of Primate Biology in Florida and was continuing at Yale, showed that the amygdala, *not* the Papez circuit, is involved in taming and changes in sexual behavior that follow a temporal lobe removal. Nor did hippocampal removals in humans produce any effects on experiencing or expressing their feelings. Furthermore, removals of the hippocampus have devastating effects on a specific kind of memory, effects that I'll take up below and in Chapter 15.

However, in totally different sets of experiments the hippocampus has been shown to be intimately involved in processing stress by regulating the pituitary-adrenal hormonal system, a finding that needs to be incorporated in any attempt to understand the role of the limbic systems in organizing emotions.

## Anatomical Fundamentals

A brief review of the brain anatomy relevant to the processes organized by the frontolimbic forebrain can be helpful at this point:

We can visualize the central nervous system as a long tube which is fabricated during our embryonic development from the same layer of cells that elsewhere makes up our skin. This tube is lined with stem cells and within the tube flows the cerebrospinal fluid. The lower part of the tube makes up our spinal cord. Where the tube enters our skull through a big hole—in Latin, *foramen magnum*— the tube becomes our brain stem. The hind part of the brain stem is called the "hindbrain"; the mid part of the brain stem is the "midbrain"; and the forward part is the "fore-brain." The most forward part of the forebrain is made up of the "basal ganglia."

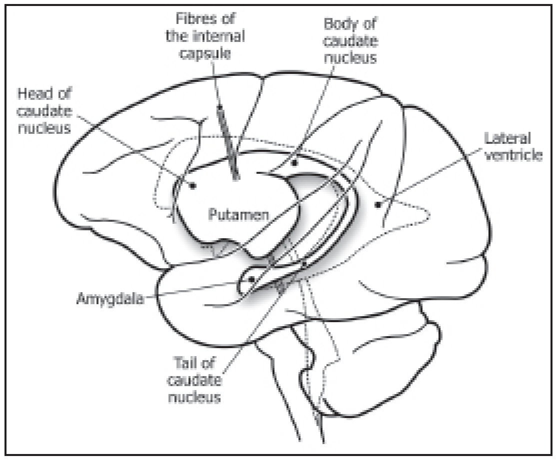
The basal ganglia can be divided into three components: An upper, a middle, and a limbic (from the Latin, *limbus*, "border"). The upper component is made up of the caudate (Latin, "tailed") nucleus and the putamen (Latin, "pillow"). The middle component is the globus pallidus ("pale glob"). The limbic component is made up of the nucleus accumbens (Latin, "lying down") and the amygdala (Greek, "the almond").

The brain cortex makes up two hemispheres that have developed in the embryo by a migration of cells from the basal ganglia. Six layers of cells migrate from the upper basal ganglia to make up most of the cortex technically called the “iso” (Latin for “uniform”) cortex. A more common name for this expanse of cortex is “neocortex” (new cortex), but as I described earlier in this chapter, this more common name is misleading in some of its usages. The remainder of the cortex is called the “allo” (Latin for “other”) cortex. The allocortex is formed when cells from the amygdala and other limbic basal ganglia migrate. These migrations sometimes do not occur at all; but for the most part, they make up a three-layered cortex. Sometimes, however, there is a doubling of three layers as in the cingulate (Latin, “belt”) cortex.

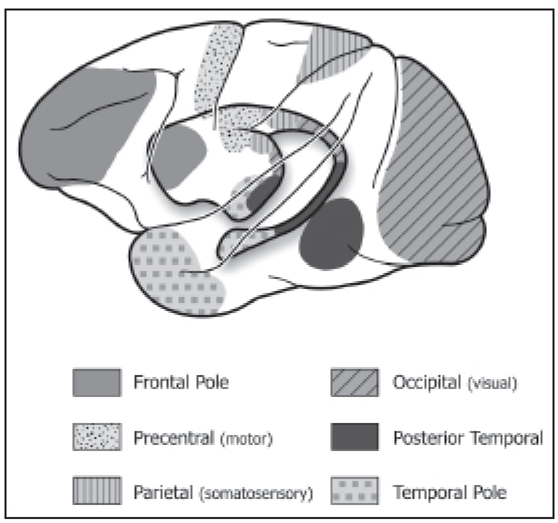
## Mistaken Identities

The limbic basal ganglia and their allo-cortical extensions are called “limbic” because they are located at the medial limbus (Latin, “border”) of the hemispheres of the forebrain. When I started my research in the late 1940s, this term was used mainly for the cingulate cortex lying on the upper part of the inner surface of the brain’s hemispheres. But also, Paul Broca, the noted 19th-century neurologist, had discerned that the allocortex formed a ring around the inside border of the brain’s hemispheres. However, until the 1950s, the allocortex was generally referred to by neuro-anatomists as the “olfactory” or “smell” brain because it receives a direct input from the nose.

Today, what was then called the “olfactory brain” is called the “limbic system” and “everyone *knows*” that our emotions are organized by our limbic brain. But what constitutes what neuroscientists call the limbic system varies to some considerable extent, and the relationship of the various parts of the limbic system to emotion is, at times, considerably distorted. Thus the popular view has built-in difficulties. The amygdala is only one structure among those loosely thought of as the limbic forebrain. In fact, originally the amygdala was not included at all in the limbic circuitry. Rather, two sources converged to be baptized by Paul MacLean as the “limbic systems.” As noted above, one source was Paul Broca who had discerned a rim of cortex around the internal edge of the cerebral hemispheres to be different from the rest of the cerebral mantle. This cortex appeared paler and was later shown to have only three layers rather than six. He called this rim of cortex ”*le grande lobe limbique.*”




*58. Upper and limbic basal ganglia*




*59. Cortical projection from the basal ganglia*

The other source, described by J. W. Papez, consisted of the hippocampus, its downstream connections through the septal region to the mammillary bodies of the hypothalamus, thence to the anterior nuclei of the thalamus which is the origin of a projection to the cortex of the cingulate gyrus, which had been labeled the “limbic” cortex. The cingulate cortex, in turn, feeds back into the hippocampus. Papez reasoned that emotions tend to go round and round and this anatomical circuit does just that.

MacLean's limbic system encompassed Broca's cortex and Papez circuitry, and originally did not include the amygdala. It was not until MacLean joined my project in John Fulton's department at Yale that it became imperative on the basis of my results to include the amygdala in any circuitry that presumably organizes our emotions. This inclusion totally changed what had hitherto been thought of as the limbic forebrain.

## The Prefrontal Cortex

In addition to experimentally defining the limbic systems, my research established the essential relationship of the anterior frontal cortex, usually called the prefrontal cortex, to those limbic systems. The finding, noted earlier, that a mediobasal limbic motor cortex surrounds the prefrontal cortex suggested that such a relationship existed. However, the definitive study came from my analysis of the thalamo-cortical input to the prefrontal cortex. The thalamus, the halfway house of sensory input to the cortex, is a three-dimensional structure. The brain cortex is essentially a two-dimensional sheet of cells and their connecting fibers. Anatomical projections that connect thalamus and cortex must therefore "lose," enfold, one dimension. This means that one thalamic dimension disappears in its projection to cortex. For most of the forebrain, the dimension "lost" is what in the thalamus is a medial to lateral dimension; front-to-back and up-and-down dimensions are maintained in the projection so that the thalamic organization and the cortical terminus of the thalamic input remain essentially unchanged.

Not so for the thalamic projections to the limbic and prefrontal cortex. The thalamic dimension "lost" in the projection is the front-to-back dimension. For instance, a long file of cells reaching from the front to the back of the thalamus projects to a point on the tip of the prefrontal cortex in primates.

This result defines an *essential* difference between the frontolimbic forebrain and the posterior convexity of the brain. As the next chapters will show, *this difference is as important for processing the brain/behavior relationship as that between the right and left hemispheres of the brain*.

## In Summary

1. The idea that the neocortex is responsible for organizing our cognitive reasoning, while the older cortical formations are solely responsible for generating our baser emotions and motivations, does not hold up. In primates, including us, the neocortex adjacent to the older cortex is very much involved in organizing the visceral and endocrine processes that presumably underlie (or at least accompany) our emotions and motivations. *This finding calls into question the presumed primitive nature of our emotions and motivations*.
2. The olfactory systems of our brain, now called the "limbic systems," are composed of two distinct systems. One system is based on the amygdala, a basal ganglion, the other on the hippocampus.
3. The basal ganglia of the brain can be divided into three constellations: an upper, a mid and a limbic. This chapter reviewed evidence that the limbic basal ganglia—the amygdala, accumbens and related structures—are involved in organizing visceral and endocrine responses presumably critical to emotional experience and behavior.
4. But direct evidence of the involvement of limbic basal ganglia in emotions had, as yet, not been obtained. The next chapters describe evidence that leads to the conclusion that the limbic basal ganglia are involved in emotions and that the upper basal ganglia—the caudate nucleus and the putamen—are involved in organizing motivational behavior.
5. The hippocampus, an intimate constituent of the Papez circuit, plays an important role in the chemical regulation of the pituitary/adrenal/ hormonal response to stress. Electrical and chemical stimulations showed that there is a large input from other parts of our cortex to the hippo-campus but that its output goes mostly to other limbic system structures.
6. However, the effects of damage to the Papez hippocampal circuit are much more drastic on certain aspects of memory than on emotion or motivation. This poses the question of how the response to stress, and therefore the Papez circuit, relates to memory and, in turn, how memory relates to emotion and motivation.

By 1958, when I moved to Stanford University, I had achieved a good grasp of the neuroanatomy and electrophysiology of what came to be known as the limbic forebrain and had written several well-received papers reviewing my findings. However, the relationships of the different limbic structures to behavior remained rudimentary. The research that I undertook to *begin* to understand these relationships is reviewed in the next chapter.

# Chapter 11
## The Four Fs

Wherein the experimental analysis of the brain systems involved in fighting, fleeing, feeding and sex, the "Four Fs," are recounted.

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> *First I shall do some experiments before I proceed further, because my intention is to cite experience first and then with reasoning show why such experience is bound to operate in such a way. And this is the true rule by which those who speculate about the effects of nature must proceed.*
>
> —Leonardo da Vinci, c. 1513 from Fritjof Capra, *"The Science of Leonardo"*

The brain processes that organize our feelings do not "feel like" those feelings. In early stages of science, we expect that our brains and bodies, as well as our physical universe, resemble what we experience every day. Thus we are pleased when we are able to correlate a specific aspect of an experience with a specific brain system. But when we examine the patterns that make up our experience and those that make up that brain system, the match between patterns is not evident. Transformations occur between the patterns that *initiate* our experiences and those that *process* the experiences. The brain processes that organize our feelings are not as we "picture" them.

The television process provides a good example of the difference between what we experience and the processes that make the experiences possible. At the beginning of the process is a scene and at the end is a picture of that scene. But that is not all there is to television (*tele* is Greek for "far" or "far off"). We need to consider the steps from the broadcasting studio, where a scene is transformed into a code that can be transmitted, to the decoding transformation at the receiver; and then the transformation that activates a screen, in order to understand how the picture on the screen is generated so that it corresponds to the scene in the studio. For the brain/behavior/experience relationship it is the same: we need to specify the transformations that make the relationship possible.

In the mid-20th century, the zeitgeist in experimental psychology was behaviorist: any terminology that referred to our subjective experiences—terms such as "fear," "joy," "hunger"—was taboo. At the time I too, heartily approved of these restrictions in terminology and decided to employ only "operational" descriptions to characterize my results of the experimental analysis of the taming and the other effects in monkeys following the removal of the amygdala.

In the 1920s and 1930s, Walter Cannon had described the outcome of his hypothalamic stimulations as resulting in "fight and flight" responses. For symptoms that followed removal of the amygdala—the taming, the increase in sexual mounting, and repetitiously putting things in their mouths—I added two responses to Cannon's "fight and flight" to make up "Four Fs": Fighting, Fleeing, Feeding and Sex.

This characterization immediately became popular and still is. In the mid-1950s, when I gave a series of lectures on this topic at the University of Michigan, my initial audience was a mere 100 students and faculty. By the end of the week, we had to move the lectures to an auditorium seating 1,000, and all the seats were filled.

For the 1960 *Annual Reviews of Psychology,* I wrote up the essence of what had been discovered in my laboratory during the 1950s at Yale University regarding these Four F's. A few skirmishes with the editors ensued: the four-letter-word revolution at Berkeley had not as yet occurred. (Of course, for the uptight, the fourth F could stand for fornication.) Fortunately for me, the *Annual Reviews* were published in Palo Alto, near my Stanford laboratory, and by personally supervising the final draft just prior to the typesetting of the paper, I was able to have the last word.

While at Yale, I had aimed to seriously quantify the behaviors that made up the Four Fs. For instance, I wanted to know what caused those monkeys whose amygdalas had been removed to put everything into their mouths. Could it be that they had lost their sense of taste and therefore were sampling everything? These monkeys would eat hot dogs, whereas normal monkeys, who are not fond of meat, might take a bite and stop eating. In order to test the monkeys' ability to taste, Muriel Bagshaw, a Yale medical student, and I set up a series of drinking flasks, each with a greater dilution of quinine (aka tonic) water and let the monkeys choose which flasks they would drink from. Using this technique, we showed something that at the time had not been discovered: the part of the brain involved in discriminating taste was located in the cortex buried within the lateral fissure of the anterior part of the temporal lobe near, but not in, the amygdala.

In another set of experiments, we used rats. John Bro-beck, a colleague of mine at Yale who later became head of the Department of Physiology at Johns Hopkins University, was an expert in making electrolytic lesions (a fancy term for burning a hole) in the hypothalamic region—which is connected to the amygdala by way of two tracts—lesions which resulted in the rats eating and eating and eating. Bro-beck was looking at changes in the rats' metabolism that were related to the excessive eating behavior. He was the perfect collaborator for me to study the possible metabolic "causes" of changes in eating behavior following the effects of the temporal lobe removals on eating. We were joined by a postdoctoral fellow from India, Bal Anand, who many years later would become the head of the All India Institute of Medical Sciences.

At Yale, we three set up our experiment. The results were a disaster mitigated by an unexpected silver lining. First, I tried to remove the rats' amygdala, the part of the medial temporal lobe that I'd been removing in monkeys. Rats have very small brains—no temporal lobes, and their amygdalas are spread out and therefore difficult to remove without damaging other brain structures. Surgery didn't work, so Brobeck went to work with his electrolytic lesions. Now the rats refused to eat at all!—just the opposite of what I'd found in my earlier tests with monkeys.

For the behavioral part of our study, pre-operatively I set up drinking flasks for the rats, just as Bagshaw and I had done for monkeys: The rats loved the quinine (tonic) water and several of them drank themselves sick. I also provided the rats with a choice between their daily ration and one that looked like (and had the consistency of) their usual food but was made up of axle grease and sawdust. The rats loved the new "food" and made themselves sick gorging on it. Once they had become sick, whether from quinine or axle grease, they never touched either again. Thus they would make a poor control group for this experiment. Furthermore, the removal of the amygdala might make the rats deathly ill because they would not stop eating or drinking, not because they had lost their sense of taste. Just making rats sick was not our intention. These tests were obviously not going to work for our experiment.

This set of preliminaries to undertaking our experiments had taken well over a year, and Anand soon would have to return to India. There were no results from all our work. I suggested that Anand do an anatomical study before returning to India, to see how many of Brobeck's electrolytic lesions had hit their target: the amygdala. Brobeck was not enthusiastic: He'd been doing electrolytic lesions in the hypothalamic region for years, first at Northwestern University and then at Yale, and had almost always produced the expected results: rats that overate. But why not section the brains of the rats anyway, to locate the sites of the electrolytically produced lesions? That way Anand would learn the technique and would have something to show for his time at Yale.

## Surprises

The anatomy was done on both the overeating rats and the ones that had stopped eating. Surprise #1: Hardly any of the lesions that had produced the overeating were in the expected location (the ventromedial nucleus) in the hypothalamic region. They were in the vicinity, but not "in," the nucleus. This confirmed, for me, a long-held view that a nucleus isn't a "center," a local place, at all: the cells that make up the "nucleus" are spread over a fairly long distance up and down the hypothalamic region. This was later ascertained by a stain that specializes in picking out the cells of this nucleus.

Surprise #2: The electrodes that Brobeck had aimed at the amygdala had gone far afield—the lesions made with these electrodes were located halfway between those that had been aimed at the hypothalamic region and those that had been aimed at the amygdala. Thus, Anand and Brobeck had obtained an important result: they had discovered a new region, a region that influenced eating behavior, which they dubbed the "far-lateral" hypothalamic region. The results were published in the *Journal of Neurophysiology* with an introductory note acknowledging my role in the experiment, and they were quoted for many years to come.

But the story does not end here. Shortly after the publication of this paper, Philip Teitelbaum, then a young doctoral student at Johns Hopkins, became intrigued with the "stop eating" effect and got his rats to eat and drink enough to tide them over the initial period after surgery. He did this by giving the rats sugar water and chocolate candy. At a meeting, he reported the results as having been produced by lesions in the far-lateral nucleus of the hypothalamus and I stood up, noted his excellent work, and went on to point out that the locus of the electrolytic lesions in the Anand and Brobeck experiments (for which I'd supervised the anatomy) and presumably in Teitelbaum's, were located in white matter consisting of nerve fibers, not of cells, and that there really was no such "far-lateral hypothalamic nucleus." At that time we didn't know where those nerve fibers originated or ended. Teitelbaum has told me on several occasions since that he was totally shaken by my comment.

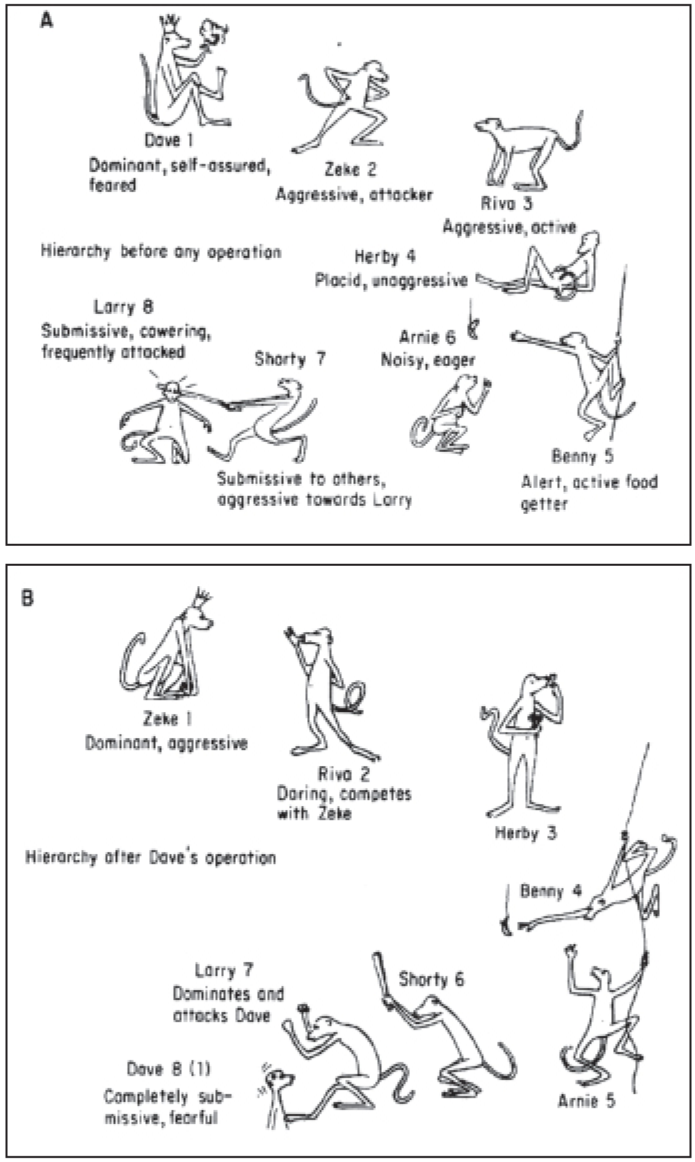
He persisted nonetheless, and we know now, through his efforts and those of others, that these fiber tracts connect places in the brain stem with the basal ganglia; that they are an important part of the dopamine system which, when the system becomes diseased, accounts for Parkinsonism.

Anand established the meaning of these results. He went back to India and pursued the research he had started at Yale using electrical recordings made from the regions he had studied there. In his India experiments, he found that as a rat ate, the electrical activity of its medial region progressively increased while that of its lateral region progressively decreased. During abstinence, the opposite occurs: the rat's lateral region becomes progressively more active while the medial region becomes progressively more quiescent. His experiments demonstrated that there is a seesaw, reciprocal relationship: The medial region serves a satiety process; the lateral region serves an appetitive process. This reciprocal relationship applies to drinking as well as to eating.

## Hit or Run?

The experimental results of our studies of "fighting" and "fleeing" behavior were equally rewarding. At Yale we set up several colonies of young male monkeys and selected one of these colonies in which the monkeys clearly formed a dominance hierarchy. We had developed quantitative measures of dominance based on procedures used by Rains Wallace, a friend of mine who was chief of the research institute representing the insurance companies in Hartford, Connecticut, where I lived at the time. Wallace had found that, in order to quantify social behavior that is almost always determined by a variety of factors (in the insurance case, factors involved in injury or death)— one must choose an "anchor." The anchor chosen must be the most obvious or the most easily measurable behavior. Then other behaviors that might influence the factor we are studying (in our case, dominance) can be rated with respect to the behavior we have chosen as an anchor. As an anchor in our experiment with the dominance hierarchy of monkeys, I chose the number of peanuts each monkey picked up when the peanuts were dropped into their cage one by one. We also used the order in which each monkey grabbed the peanut, followed by other "subsidiary" measures such as facial grimace, body posture of threat, and actual displacement of one monkey by another. We filmed all of this so that we could study the films frame by frame.

I removed the amygdalas (of both hemispheres of his brain) of the most dominant monkey in the colony. As expected, he gradually fell to the bottom of the hierarchy, but it took about 48 hours for his fall to be completed. Other monkeys were challenging him, and he seemed not to know how to meet these challenges.



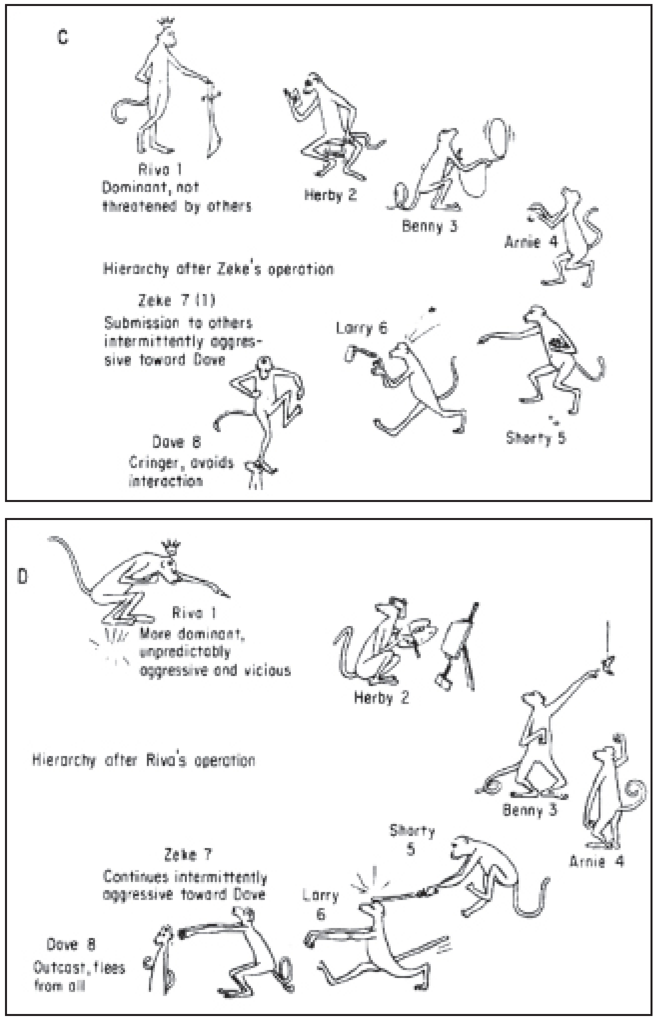

*60. A: dominance hierarchy of a colony of eight preadolescent male rhesus monkeys before any surgical intervention. B: same as A after bilateral amygdalectomy had been performed on Dave. Note his drop to the bottom of the hierarchy. (From Pribran, 1962)*

Next, I operated on the monkey who had replaced the first as the most dominant. The result regarding the change in the order of dominance was essentially the same. To be certain that our results would be generally applicable, I then operated on the monkey that had originally been third in the hierarchy. Surprise! He became more aggressive and maintained his dominance. Of course, my colleagues accused me of sloppy surgery. We had to wait a few years (while the monkeys were used in other experiments) before an autopsy showed that my removal of the amygdala was as complete in the third monkey as it had been in the first two monkeys I had operated upon.

When my Yale collaborators, Enger Rosvold, Alan Mirsky and I were later reviewing our films of the monkeys' interactions after their surgery, we found that in the case of the third monkey no *challenges* to his dominance had occurred. The next monkey in line—monkey #4—was a peacenik, happy to get his share of food and water without troubling the other monkeys.

## Brain Surgery and Social Context

Over and over, my experience with removals of the frontal and limbic parts of the brain had demonstrated, as in this instance, that such vulnerability to social context occurs during the immediate postoperative period. Dramatic changes in behavior can be produced immediately postoperatively by social input. Lawrence Weiskrantz—at that time a Harvard graduate student in psychology, doing his dissertation experiments in my laboratory—and I informally tested this observation: After surgery, I approached the monkey in a docile fashion, always keeping my head below his level, and withdrawing when he approached. The monkey became his old belligerent rhesus self and even more so—grimacing and attacking an approaching figure or hand. By contrast, using another monkey who had had his amygdala removed in the same fashion, Weiskrantz behaved firmly and assertively. His monkey became docile, and we all had him eating out of our hand.




*61. C: same as A and B, except that both Dave and Zeke have received bilatral amygdalectomies. D: final social hierarchy after Dave, Zeke, and Riva have all had bilateral amygdalectomies. Note that Riva fails to fall in the hierarchy. Minimal differences in extent of locus of the resections do not correlate with differences in the behavioral results. The disparity has been shown in subsequent experiments to be due to Herby's nonagressive "personality" in the second position of the hierarchy. (From Pribram, 1962.)*

Our Yale dominance experiment has been quoted over the years in many social psychology texts. The significance of the results became especially important when the Assistant District Attorney of the State of California was heard to suggest that removal of the amygdala might be a treatment of choice for the hardened violent criminals populating our jails. I called him to alert him to our results—that the criminals might become even more vicious, unless the postoperative social situation was very carefully established, and that we didn't really know how to do this. Luckily, the matter was quickly dropped like the hot potato it was. It was the mid-1960s and I was concerned that someone might recommend brain surgery for the "revolutionary" students on our campuses.

*Brain surgery does not remove "centers" for aggression, fear, sex, etc. Ordinarily brain processes* enable *certain behaviors and, once engaged, help to organize and reorganize those behaviors.*

There is a difference however when our brain becomes injured and "scars" form, for instance when scars produce temporal lobe epilepsy: some patients occasionally have uncontrollable episodes during which they become violent, even to the extent of committing rape or murder. Once the seizure is over, the patient returns to being a docile and productive person. If the patient recalls the period of his seizure—though most do not—or when evidence of how he behaved is shown to him, he is terribly upset and remorseful, and will often request surgical relief if the seizures have become repetitive.

## The Fourth F

As we were studying at Yale the effects of amygdalectomy on dominance and on eating and drinking similar experiments were being performed at Johns Hopkins University in the Department of Physiology and in the Army Research Laboratories at Walter Reed Hospital in Washington, DC. In addition, both of these research groups were studying the effects of amygdalectomy on sexual behavior in cats. At Hopkins, there was no evidence of change in sexual behavior after the surgical removal. By contrast, at the Army Laboratories, as in Klüver's original report of his and Bucy's experiments on monkeys in Chicago, "hypersexuality" followed the removal of the amygdala in cats.

I paid a visit to my friends in the Department of Physiology at Hopkins and looked at the results of their surgical removals, which were identical in extent to mine. I looked at their animals—cats in this case rather than monkeys. The cats were housed in the dark basement of the laboratory in cages with solid metal walls. Anyone planning to handle the cats was warned to wear thick gloves. When the cats were looking out through the front bars of the cage, the experimenters would blow into their faces to test for taming: the cats hissed. Attempts to grab the cats resulted in much snarling, clawing and biting.

I then traveled 30 miles from Baltimore to Washington to visit my friends at the Walter Reed Medical Research Center, where they were also removing the amygdalas from the brains of cats. The brain surgery had been well carried out and appeared, in every respect, identical to what I had seen at Hopkins. But the situation in which these cats were housed was totally different. These cats were kept in a large compound shared with other cats as well as with other animals—including porcupines! The animals were playing, wrestling, eating and drinking. My host, who was in charge of the experiments, approached one of the cats who cuddled to him. To my consternation, he then tossed the cat into a corner of the compound, where the cat cowered for a while before rejoining the other animals in their activities. "See how tame these cats are? The experimenters at Hopkins must have missed the amygdala." By now, the cats had resumed their mounting behavior, including a very patient and forgiving porcupine who kept its quills thoroughly sheathed while a "hypersexed" tabby tried to climb on top of it.

I wrote up this story of the Baltimore and Washington cats for the *Annual Reviews of Psychology*, again emphasizing that it is the social setting and not the extent or exact placement of the brain removal that is responsible for the differing outcomes we find after the surgery.

I was able to add another important facet to the story: experiments that were done at the University of California at Los Angeles on a set of "Hollywood cats." This time, the experimenters had studied normal cats. They were placed in a large cage that took up most of a room. There were objects in the cage, including a fence at the rear of the cage. The behavior of the cats was monitored all day and all night. The UCLA experimenters found what most of us are already aware of: that cats go prowling at night, yowling, and, (what we didn't know) mounting anything and everything around! After the brain surgery this nocturnal behavior took place during the day as well. Testosterone levels were up a bit. However, in our experiments with monkeys at Yale, we had shown that while testosterone elevations amplify sexual behavior such as mounting once it has been initiated, these elevated levels do not lead to the initiation and therefore the frequency of occurrence of sexual behavior. Today we have the same result in humans from Viagra.

The Hollywood cats thus showed that the removal of the amygdalas influenced the territory, the boundaries of the terrain within which sexual behavior was taking place. Although an increase in sexuality due to an increase in hormone level might have played a role in amplifying sexual activity, *the increase in that behavior might also have resulted in the modest increase in sexual hormone secretion*. By far, the more obvious result was a change in the situation—day vs. night—in which the cats were doing It: For ordinary cats, night is the familiar time to practice the fourth F. For the cats who had been operated upon, every situation was equally familiar and/or unfamiliar. It is the territorial pattern, the boundary which forms the context within which the behavior occurs, that has been altered by the surgery, not the chemistry that fuels the behavior.

## Basic Instincts

In light of all these results, how were we to characterize the Four Fs? On one of my several visits with Konrad Lorenz, I asked him whether the old term "instinct" might be an appropriate label for the Four Fs. The term had been abandoned in favor of "species-specific behavior" because if behavior is species specific, its genetic origins can be established. I had noted during my lectures at Yale that if one uses the term instinct for species-specific behavior, human language is an instinct. This usage of the word is totally different from its earlier meaning. Nevertheless, Steven Pinker, professor of linguistics at MIT, has recently published a most successful book entitled *The Language Instinct*.

My suggestion to Lorenz was that we might use the term "instinct" for species-shared behaviors. What makes the studies of birds and bees by ethologists like Lorenz so interesting is that we also see some of these basic patterns of behavior in ourselves. Falling in love at first sight has some similarities to imprinting in geese, the observation that Lorenz is famous for. Sir Patrick Bateson of Cambridge University, who, earlier in his career, was one of my postdoctoral students at Stanford, has shown how ordinary perception and imprinting follow similar basic developmental sequences.

Lorenz agreed that my suggestion was a good one, but felt that it might be a lost cause in the face of the behaviorist zeitgeist. His view was also expressed by Frank Beach in a presidential address to the American Psychological Association in a paper, "The Descent of Instinct."

Thus, the Four Fs, though they have something to do with emotional (and motivational) feeling, can be described behaviorally as basic instincts or dispositions. These dispositions appear to be a form of a hedonic- (pleasure and pain) based memory that, as we shall shortly see, directs attention in the process of organizing emotions and motivations. As an alternative to "basic instincts," the concept "dispositions" captures the essence of our experimental findings regarding the Four Fs. Webster's dictionary notes that dispositions are tendencies, aptitudes and propensities. Motivations and emotions are dispositions.

The brain processes that form these hedonically based dispositions are the focus of the next chapters.

# Chapter 12
## Freud's Project

Wherein I take a detour into the last decade of the 19th century to find important insights into emotional and motivational coping processes.

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> *One evening last week while I was hard at work, tormented with just that amount of pain that seems to be the best state to make my brain function, the barriers were suddenly lifted, the veil was drawn aside, and I had a clear vision from the details of the neuroses to the conditions that make consciousness possible. Everything seemed to connect up, the whole worked well together, and one had the impression that the thing was now really a machine and would soon go by itself.*
>
> —Sigmund Freud, letter to Wilhelm Fliess, October 20, 1895

As I was moving from Yale to Stanford in the late 1950s, I had just disproved Köhler's DC theory of the brain as responsible for perception, and I had arrived at an impasse regarding the "how" of the Four Fs. I had put up a successful behaviorist front: One of my Yale colleagues, Danny Friedman, asked me why I'd moved to Stanford. He truly felt that I'd come down a step or two in Academe by moving there. He remarked, "You are a legend in your own time." If that was true, it was probably because I gave up a lucrative career as a neurosurgeon for the chance to do research and to teach. My initial salaries in research were one tenth of what I was able to earn in brain surgery. But I was accomplishing what I wanted through my research: I had been accepted in academic psychology and had received a tenured academic position, held jointly in the Department of Psychology and in the Medical School at Stanford.

At that time, "The Farm," as Stanford is tenderly called, really was that. What is now Silicon Valley, a place of "concrete" technology, was then Apricot Valley (pronounced "aypricot") with miles of trees in every direction. Stanford Medical School's reputation was nonexistent: that's why a whole new faculty, including me, was put in place when the school was moved southward from San Francisco to the Stanford campus in Palo Alto. Our first concern at the Medical School: How will we ever fill the beds at the hospital? A heliport was established to bring in patients from afar and advertisements were sent out to alert central and northern California residents that we were "open for business." How different it was then from when, 30 years later, I would become emeritus and leave California to return to the East Coast.

I had succeeded Lashley as head of the Yerkes Laboratory of Primate Biology in Florida and Robert Yerkes had become my friend during the negotiations for my appointment. Still, I had encountered insurmountable problems in trying to obtain university appointments for prospective research personnel at the Laboratory because of its distance from any university. I had been equally unsuccessful in moving the laboratory to a friendly university campus where teaching appointments could be obtained.

I felt that research institutions, unless very large (such as NIH or the Max Planck), become isolated from a broader scope of inquiry that a university can provide, and thus, over time, become inbred and fail to continue to perform creatively. I had tried to convince Harvard to accept a plan I had developed to move the Laboratory to a warehouse in Cambridge, since Harvard had a stake in the Laboratory; Lashley's professorship was at Harvard. Harvard faculty had nominated me for a tenure position three times in three different departments (psychology, neurology and even social relations), but the faculty recommendations were not approved by the administration.

All effort in these directions was suddenly halted when Yale sold the Laboratory to Emory University (for a dollar) without consulting the board of directors. This was in keeping with the administrative direction Yale was taking: the Department of Physiology had already shifted its focus from the brain sciences to biochemistry, and the president had mandated loosening Yale's ties (that included remanding tenured professorships) to the Laboratory and other institutions that were mainly supported by outside funding.

The time was ripe to "Go West, young man" where other luminaries in psychology—Ernest (Jack) Hilgard, dean of Graduate Studies, and Robert Sears, the head of the Department of Psychology, at Stanford—had been preparing the way.

## Hello, Freud

Despite my so-called legendary fame and the administrative disappointments at Yale and Harvard, the issue that bothered me most, as I was moving to Stanford, was that I still really didn't understand how the brain worked. In discussions with Jerry Bruner, whose house my family and I rented for that summer while I taught at Harvard, he recommended that I read Chapter 7 of Freud's *Interpretation of Dreams*. I also read the recently published biography of Freud by Ernest Jones, who mentioned that someone knowledgeable about the brain should take a look at Freud's hitherto neglected *Project for a Scientific Psychology*, the English translation of which had been published only a few years earlier in 1954. I read the *Project* and was surprised by two important insights that Freud had proposed:

1. Motivation is the "prospective aspect of memory." At that time, psychologists were focused on internal "drives" as the main source of motivation, a conception my laboratory experiments and those of others had already found wanting; and

2. Brain circuitry involves action potentials, resistance, and local graded activity. My theoretical work had emphasized electrical field potentials that were characteristic of the brain's fine- fibered, dendritic, deep structure—and here was Freud, a half century earlier, already aware of the importance of this aspect of brain processing.

I immediately set to work on a paper, calling *Freud's Project* a "Rosetta stone" for understanding psychoanalysis. My paper emphasized the memory-motive structure and local graded activity, the field potentials in the brain which was translated into English as "cathexis." I found fascinating insights into how a late-19th-century neurologist could view brain function. Freud had struggled with the problem of form in terms of quantity vs. quality. He showed that an adrenaline-like *quantitative* chemical buildup resulted in anxiety—"unpleasure" in the translation. Anxiety, Freud indicated, was controlled by way of the memory-motive circuitry in the basal (ganglia of the) forebrain. *Qualities*, Freud wrote, composed consciousness enabled by processes operating at the brain's surface, its cortex. The cortical processes were not made up of circuits but of "patterns of periodicity," of energy transmitted from our sensory receptors.

I had been suggesting that an essential part of cortical processing was holographic-like—that is, based on interference patterns formed by frequencies of waves. Frequencies are the reciprocals of Freud's patterns of periodicity. I was stunned and elated. It is helpful to find that one's scientific views are recurrently confirmed under a variety of experimental conditions.

The publication of my paper, entitled "The Neuro-psychology of Sigmund Freud" in the book *Experimental Foundations of Clinical Psychology*, would lead to a ten-year study of the *Project* in a partnership with Merton Gill, the eminent psychoanalytic scholar. Our book, *Freud's "Project" Re-assessed,* was the fruit of this effort. It was great fun: the last sentence in the book reads "—and our views (about the virtue of the future place of psychoanalysis as a natural science) are irreconcilable."

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# The "Project" Reassessed

Gill was at Berkeley and I at Stanford. When he first read my paper, he congratulated me on having finally become a scholar, not just a bench scientist. He noted, however that I'd made 27 errors in my not-so-very-long paper. I was upset and went to work to correct the errors. After a month, I wrote a reply to Merton, saying that I was grateful for his critique and that he was correct in 7 of his criticisms—but the other 20 were his errors, not mine. After a few more exchanges like this, I decided to telephone him. I suggested that since we were just across San Francisco Bay from each other we might meet, which we did—alternating between Berkeley and Stanford every Friday afternoon for the next two years. We scrupulously studied both the English and German texts and compared them. German was my native language, and Merton's knowledge of Freud's later work was critical: we needed to see how many of the early ideas contained in the *Project* had later been abandoned or changed. Surprisingly few.

After two years of work, Merton and I had a stack of notes taller than either of us. What to do? I said, let's write a book. I quickly disabused Merton of writing voluminous footnotes, as was then the fashion in psychoanalysis. From George Miller I had inherited the motto: "If it's important, put it into the text. If not, leave it out." Merton and I each wrote chapters—and after a first draft we started critiquing each other's chapters and produced another set of notes. I used them to write another draft. More critique from Gill. I wrote up a third draft.

Silence. After two weeks I called Gill: He hadn't read the draft. He was sick of the *Project*, and never wanted to hear of it again. I could do anything I wanted with our work. The only stipulation was that I would never mention his name in connection with it. He could not give me any reasons for his change of heart; all he could say was that he was tired of the work. I was dismayed, but I did as he asked in the two more papers that I wrote, saying only that I was deeply indebted to M. G., who didn't want me to mention him.

## Resurrection

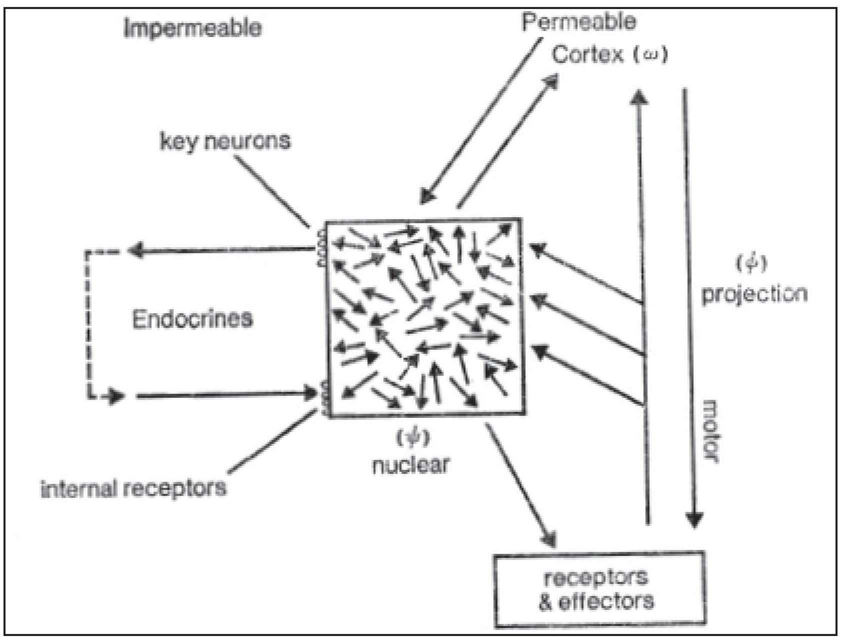
A decade passed, and I was asked to give the keynote address at the meeting of the International Psychoanalytic Society in Hawaii. I felt deeply honored and accepted the invitation. Next, I was asked who might introduce me. Merton Gill seemed to be the perfect person. I called Gill, now in New York. He told me that he had moved from Berkeley shortly after we had last talked and had been depressed and hadn't given a talk in ten years, but that he felt honored that I was asking him to introduce me! Gill, the curmudgeon, feeling honored? The world was turning topsy-turvy. He asked that I send him some of my recent brain physiology studies so he'd be up to date. I replied that no, I wasn't going to present those. What I wanted to do was to present the findings in our book. Did he still have a copy of the last draft? Search. "Here it is in my files," he said. "Have you read it?" I asked him. "No." "Will you?" "Yes. Call me next week." I did, on Tuesday. Gill was ebullient: "Who wrote this?" I said I did. "Brilliant. Wonderful." I called back a few days later to be sure I'd actually been talking to Merton Gill. I had. All was well.

We met in Hawaii. My talk was well received, and Merton and I decided to resume our long-delayed joint effort. I felt that we needed to re-do the first chapter, which was about the death instinct—a horrible way to begin a book. Merton thought that if we could solve what Freud meant by primary and secondary processes, we would make a major contribution to psychoanalysis and to psychology. He polished the final chapter, and I went to work on the "processes" and found, much to my surprise, that they were similar to the laws of thermodynamics that were being formulated by the eminent physicist Ludwig Boltzmann in Vienna at the same time that Freud was actively formulating his ideas summarized in the *Project*.

## Freud's Ideas

During our work on the *Project* many more rewarding insights emerged about Freud's ideas. Gill was especially pleased to find that Freud had already addressed what was to become the "superego" in his later works. Freud described the "origin of all moral motives" to a baby's interaction with a caretaking person who helped the infant relieve the tensions produced by his internally generated drives. The brain representations of the actions of the *caretaking person* are therefore as primitive as those initiated by the drives. It is the function of the developing ego to bring the caretaking person into contact with the infant's drives. Gill had written a paper to that effect even before he had read the *Project*, and was therefore pleased to see this idea stated so clearly. *The* *"superego" is therefore a process during which society, in the role of a caretaking person, tries to meet and help satisfy drive-induced needs, not to suppress them.* This is contrary to the ordinary interpretation given today which holds that the 'superego' acts to suppress the 'id.'

Another gem was Freud's description of reality testing: An input is sensed by a person. The input becomes *unconsciously*—that is, automatically—processed in our memory-motive structure. A comparison between the results of the memory-motive processing and that input is then made *consciously* before action is undertaken. This "double loop of attention," as Freud called it, is necessary because action undertaken without such double-checking is apt to be faulty.




*62. Stylized representation of the "machine" or "model" of psychological processes presented in the* Project. *(From Pribram and Gill* Freud's "Project" Re-assessed*)*

In the 1880s, Helmholtz had already described such a parallel process for voluntarily moving the eyes. Freud greatly admired Helmholtz's work and was overtly trying, in the *Project,* to model a "scientific psychology" according to principles laid down by Helmholtz and Mach. In the absence of voluntary reality testing, action and thought, which for Freud was implicit action, are merely wishful. Freud defined neuroses as composed of overriding wishes. One can see, given the rich flavor of the *Project*, why I became so excited by it.

For almost a half-century I've taught a course on "the brain in the context of interpersonal relations," and I always begin with Freud. The students are as surprised and excited, as I have been, to realize that "cognitive neuroscience," as it is called today, has common threads going back to the beginning of the 19th century—threads that formed coherent tapestries toward the end of that century in the writings of Sigmund Freud and William James.

Within a year of our decision to complete our book, *Freud's "Project" Re-assessed*, Gill and I were ready for its publication, which immediately received a few nice reviews from neurologists and psychiatrists, and quite a few really bad ones from psychoanalysts. Basic Books disappointed us in its distribution, and my presentations to various psychoanalytic institutes were greeted with little enthusiasm except for those in the Washington-Baltimore Institute and the William Allison White Institute in New York, where discussions were lively and informed.

Now, over thirty years after the 1976 publication of our book, beginning on the 100th anniversary the *Project* in 1995, both have become reactivated: Psychoanalysis is returning to its neurobiological roots. There are now active neuro-psychoanalytic groups in Ghent, Belgium, and Vienna, Austria, and at the University of Michigan at Ann Arbor—and there is also a flourishing Neuropsychoanalytic institute in New York.

Freud called his *Project*, which was about the brain, as well as his later socio-cultural work, a "metapsychology." The metapsychology was not to be confused with his clinical theory, which was derived from his work with his patients. Most psychoanalysts work within Freud's clinical theory— but that is another story, some of which is addressed in Chapter 19. The current endeavors in neuro-psychoanalysis are bringing a new perspective to psychoanalysis and psychiatry. As Gill and I stated in our introduction to *Freud's "Project" Re-assessed*, Freud already had formulated a cognitive clinical psychology in the 1890s, long before the current swing of academic and practicing psychologists to cognitivism. But even more interesting to me is the fact that the *Project* is a comprehensive, well-formulated essay into cognitive neuroscience a century before the current explosion of this field of inquiry. Reading Freud and working with Merton Gill helped me, a half century ago, to reach a new perspective in my thinking about what the brain does and how it does it.

For a few years, in the mid-1960s, I would present lectures on the insights and contents of Freud's *Project as my own*—only to acknowledge to an unbelieving audience during the discussion of the presentation, that what I had told them was vintage Freud, 1895.

# Choice

# Chapter 13
## Novelty: The Capturing of Attention

Wherein I recount a set of surprising results of experiments performed in the 20th century that changed our view of how motivations and emotions are formed.

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> *When I have inserted knowledge into my mysteries or thrillers I have found that my readers think that I'm showing off and that the passage(s) interrupt the plot.*
>
> —Chair, ThrillerFest Conference, New York, June 2007

While the Freud "project" was going forward, most of my effort went into designing and carrying out experiments that would answer the question: What *brain process*, what disposition(s), did the diverse behaviors making up the Four Fs have in common?

As I was about to move to Stanford, tackling the search for a common brain process that underlies the Four Fs frontally seemed to have reached a dead end. I therefore decided to do something that is unusual in the scientific community (and certainly a course of action that would never be awarded a research grant): I decided deliberately to outflank the problem by testing monkeys in some fashion that could not be readily subsumed under the heading of the Four Fs. What would be the effects, if any, of removal of the amygdala in such a situation?

## Transfer of Training

I had recently heard a lecture on "transfer of training." The procedure consisted in first training an animal or child to choose the larger of two circles and then presenting two rectangles to see whether the animal (or human) will again choose the larger of the two without any further training. I used monkeys that had been operated on some three years earlier—their hair had grown back, and they were indistinguishable from the monkeys who had not been operated upon. I then trained all the monkeys, those who had been operated on and those who had not, to choose the paler of two gray panels set in a background of a third shade of gray. Once the monkeys were thoroughly trained, I began to substitute, approximately every fifth trial, two new panels with shades of gray that were substantially different from the gray of the original panels. A number of the monkeys chose the lighter shade of gray of the two new panels. Others chose randomly between the lighter or darker of the two new panels, as if they had not learned anything.

When I checked the surgical records of the monkeys I had tested, I was delighted: *All* the monkeys who chose *randomly* had been operated on; their amygdalas had been removed. And all the monkeys who had *transferred their training*—what they had learned—to the new task were the control animals who had never been operated upon. Here was the performance of a task that was affected by amygdalectomy and that could by no stretch of imagination be labeled as one of the Four Fs.

I had finished this experiment at Yale just before moving to Stanford. It was time to reconcile this result with those obtained on the Four Fs. Muriel Bagshaw who, as a student, had assisted me with the "taste" studies, had received her MD degree at Yale after having a baby and had relocated to the Pediatric Department at Stanford just at the time I moved my laboratory to the new Stanford Medical Center. We resumed our collaboration with enthusiasm and immediately replicated the transfer of training experiment, using circles, rectangles and other shapes. Once again, the monkeys who had their amygdalas removed were deficient on tasks that demanded transfer of training, while their memory for tasks that did not involve transfer of training had remained intact. *I surmised that what might underlie the deficits obtained in the Four F experiments is that the animals that had had their amygdalas removed failed to transfer their pre-operative experience to the postoperative situation and failed to accumulate the results of new experiences that accrued daily.*

## Growing Up

I was still not completely over my behaviorist period. Though I was "growing up," as Lashley had predicted that I someday would, and had done so to a considerable extent while Miller, Galanter and I were writing *Plans and the Structure of Behavior*, I still felt that we were buying into representations and Plans being stored and reactivated "in the brain"—and I was at a loss as to how such a process might work. I had disposed of Köhler's isomorphism and had not yet adopted Lashley's interference patterns. But for my conjecture that the disposition underlying the Four Fs has to do with transfer of training, the issue was straightforward: Does the deficit in transfer of training indicate that processes occuring in the limbic basal ganglia allow specific experiences to became represented in the brain? Lashley (who firmly supported "representations") and I had once argued this point while we were strolling down the boardwalk in Atlantic City. I can still "see" the herringbone pattern of the boards under our feet every time I think of representations—suggesting that perhaps he was right.

As I was worrying the issue of representations in the early 1960s, while I was putting together my laboratory at Stanford, Alexander Luria and Eugene Sokolov, his pupil, came from Moscow for a weeklong visit.

We three had just attended a conference in Princeton where Sokolov had presented his results, definitively demonstrating that repeated sensory inputs produce a *representation* in the brain—*a neuronal model* of the input, as he called it. Sokolov had exposed his human subjects to regular repetitions of tones or lights. Each subject had demonstrated an "orienting reaction" to the stimulation, an orienting reaction which Sokolov had measured by changes in the subject's skin conduction, heart rate, and the EEG. As Sokolov repeated the stimulation, the subject's orienting reaction to that stimulus gradually waned—that is, the subject's response habituated. Sokolov then omitted one in the series of stimuli. Leaving out the "expected" stimulus provoked an orienting reaction to the *absence* of a stimulus that was as large as the reaction the initial stimulus had produced! The reaction to the absence of a stimulus meant that the person now reacted to any change in the whole pattern of stimulation, *a pattern that had become a part of his memory. Sokolov's evidence that we construct a specific representation of the pattern of our experience was incontrovertible. We orient to a change in the familiar!!!*

But at the same time, my reservations regarding "representations" were confirmed. At the moment of response to the omitted stimulus, the response was not determined by the environmental stimulus but by the memory, the neuronal model, of prior stimulation. As we shall see in the next few chapters, there are whole brain systems devoted to storing the results of "nonstimulation." Walter Freeman, professor of neuroscience at the University of California, Berkeley, has emphasized the fact that our perceptions are as much determined by our memories as by the environmental situations we confront. Freeman had to come to this conclusion because, in his experiments, his animals did not show the same brain patterns when confronted by the same environmental patterns. As William James had put it, our experience is like a flowing river, never quite the same.

Freeman and I are good friends, and I have tremendous respect for his work and have been influenced by it. But for decades we discussed his findings, and I was always troubled by the changed brain patterns that appeared to the same stimulus in his experiments. Finally, Walter articulated clearly that it is the memory, the knowledge attained, that is as much if not more important to forming a precept as is the stimulating event itself. Sokolov's "leaving out" an expected stimulus is a simple demonstration of this finding.

Our situation is like that of the Copernicans—we grope for ways to articulate the results of our experiments, explanations that at one level we already "know." With respect to the results of the experiments on familiarization, and their relevance to emotion, these insights into what constitutes a so-called "representation" turned out to be even more significant than what constitutes a "representation" with regard to perception.

At Princeton, Sokolov had read his paper in somewhat of a monotone but in reasonably good English. By contrast, Luria had made his presentation—on the scan paths that eye movements describe when looking at a picture—with a flourish. Sokolov seemed unimpressed, twirling his eye glasses as Luria talked. I assumed that Sokolov had heard Luria many times, had "habituated" and was therefore bored. Or was he really just monitoring Luria for the KGB? We were, after all, at the height of the Cold War.

Arriving at Stanford after several stops at universities on the way, Luria appropriated my secretary and asked her to do a myriad of tasks for him. Sokolov seemed extremely impatient, in his black suit and balding head, confirming my suspicion that he might be KGB. Suddenly, Luria said he was tired and needed a nap. As we were showing him to his room, Sokolov whispered to me, "I must see you. It is urgent." Of course, I understood: he must be KGB and needed to convey to me some restrictions or warnings about Luria's rather notorious behavior. (Unbridled in his everyday transactions, he had been "rescued" several times by his wife, a chemist in good standing in the Soviet Union.)

Once Luria was tucked away for his nap, Sokolov heaved a sigh of relief and exclaimed, "That man is driving me mad. We have stopped exclusively at camera stores between Princeton and here. I need a shirt. I saw a shopping mall as we arrived. Could you please, please take me there?" So much for the KGB!

Our own State Department, which had vetted and cleared the Luria-Sokolov trip to the U.S. was a bit more serious about having me monitor them while under my custody. I was not to take Luria more than 50 miles beyond Stanford; not to Berkeley and not even to San Francisco! "Et cetera, et cetera, et cetera," as the King of Siam said in *The King and I*.

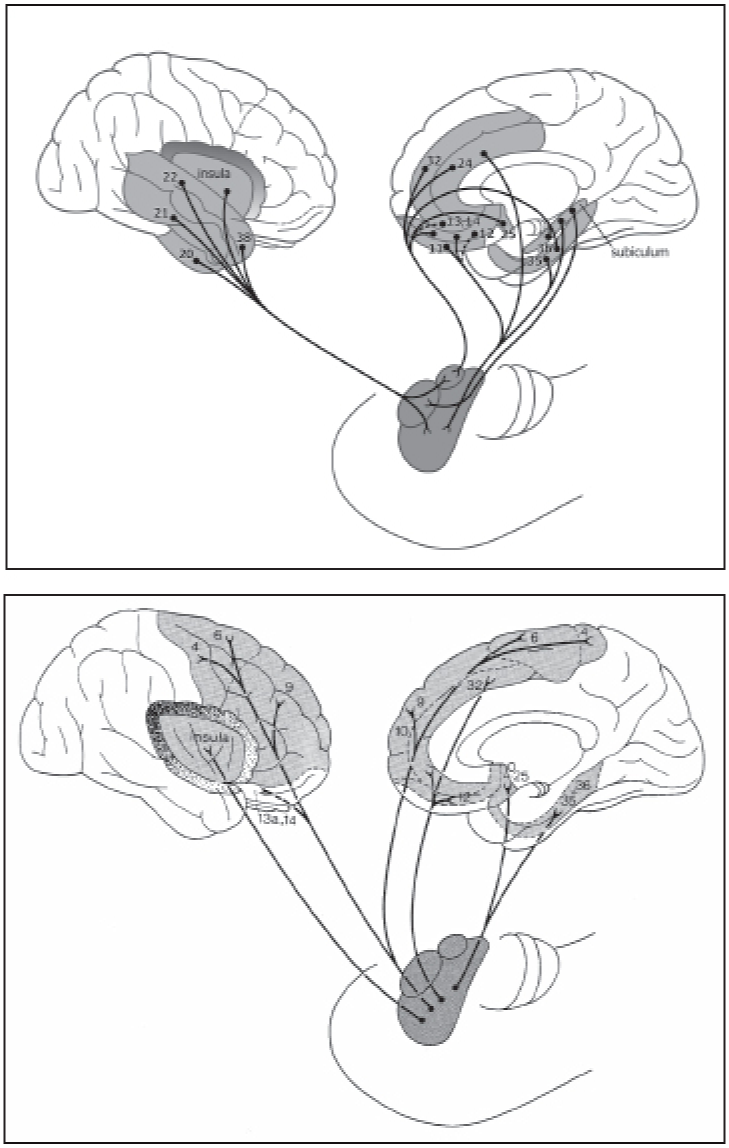
Government monitoring aside, we managed to have a wonderful week. Between planning experiments, we went on several (short) trips. I took Luria and Sokolov to Monterey to see Cannery Row; both of them had read Steinbeck. We went to a lovely little café with a garden in back, situated on a slight slope. Luria, who was facing the garden, got up and in his usual brisk manner dashed off to see it, failing to notice the outline he had left in the sliding glass door he'd crashed through! His impact was so sudden that only where he hit was the glass shattered and scattered: the rest of the door was intact. I settled with the cafe-owner— for $30. Luria was surprised that anything had happened: there was not a mark on him.

Despite government "injunctions," we did go to San Francisco: Sokolov had read all the Damon Runyan and Dashiell Hammett stories and had to see all the sites he remembered—that is, between Luria's camera store stops. We had an appointment for Luria and Sokolov to speak at Berkeley and were a bit late for their talks—but all went smoothly. I never heard from either the State Department or the KGB about our various visits.

## Orienting and Familiarization

Muriel Bagshaw and I set out to use Sokolov's indices of the orienting reaction in monkeys. Another student and I had first confirmed Sokolov's conclusions on humans. In conducting these tests, however, we had found that the placement of the heart and blood pressure monitor was critical—somewhat different results were obtained with even slightly different placements of the monitor. There is much art in experimentation —that is why I try to see for myself an experimental procedure in someone else's laboratory, or to repeat the experiments in my own laboratory, if the results of an experiment are critical to my thinking.

Over the next two decades, Bagshaw and I explored the effects of removal of the amygdala in monkeys on the orienting reaction and its subsequent habituation. In the process, we also found that classical Pavlovian conditioning is disrupted by removal of the amygdala. Our results showed that in the conditions of our experiments, both habituation and conditioning are dependent on activating the viscera (hollow organs, such as the gut, heart and lungs) of the body and the autonomic nervous system that controls those viscera. No gut-involvement, no habituation; that is, no familiarization.




*63. Afferent and Efferent Connections of the Amygdala*

Ordinarily, a novel (or reinforcing) event produces a visceral reaction largely by way of the autonomic nervous system: a galvanic skin response due to a slight increase in sweating; a brief increase in heart rate; and a change in respiratory rate. These responses “habituate,” indicating that the stimulus has become familiar: with repetition of the stimulus, the responses attain a low amplitude of waxing and waning. What surprised us is that after amygdalectomy the novel stimuli failed to habituate; that is, *the novel failed to become familiar. No representation, no "neuronal model" had been formed.*

These new observations fitted well with those I had obtained at Yale in the late 1940s, when I showed that electrical stimulation of the amygdala and the related limbic motor cortex results in changes in our heart and breathing rate, blood pressure and in gut contractions. Since then, James McGaugh of the University of California at Irvine has shown that there is a direct influence of amygdala stimulation on the secretion of adrenaline by the adrenal gland.

But just as in the case of the classical motor cortex, the behavioral function of the limbic *motor* cortex is not to regulate the visceral/autonomic functions per se, but rather to develop attractors; that is, to process targets. In the case of the classical motor cortex, these targets serve as attractors that organize an *achievement in the world we navigate, an intention-in–action*. In the case of the limbic motor cortex, the targets serve to organize an appraisal, *an assessment of the relevance to the organism of a novel input*.

Such assessments of relevance are usually explored under the term "attention." Actually, the experimental analysis of the effects of removals of the amygdala (or their stimulation) resulted, for the most part, in changes in attention, changes that had then to be related to the processing of emotion. The next sections of this chapter summarize and reorganize, in terms of what we finally achieved, what seemed to us to be a very long experimental route we had to traverse between attention and emotion.

## Something New

In 1975, Diane McGuinness, then a graduate student at the University of London, and I published a review of decades of experiments, performed around the world, that aimed to show differences in bodily responses to various emotions. McGuinness and I noted, in our review, that all the physiological measures that scientists had used to characterize differences in emotional responses in a subject ended in discovering differences in the subject's manner of *attending*. Donald Lindsley and Horace (Tid) Magoun, working at the University of California at Los Angeles (UCLA), had proposed an "activation theory of emotion" based on differing amounts of "attention" being mobilized in a situation. Thus, the results of the experiments McGuinness and I had reviewed, including those that Bagshaw and I had performed, were in some respects relevant to the processing of emotions. But exactly *how* was, before our review, far from clear.

Mc Guinness and I recalled that William James had divided attention into primary and secondary. This division was later characterized as assessing "what is it?" (primary) vs. assessing "what to do?" (secondary.) Because assessing "what is it?" *interrupts* our ongoing behavior, we described it as a "stop" process. Because assessing "what to do" *initiates* a course of action or inaction we may take, we described it as a "go" process. The experiments in my laboratory had demonstrated that the amygdala and related limbic brain systems deal with "stop," while the upper basal ganglia deal with "go" processes.

James's division of attentional processes into primary and secondary paralleled his characterization of emotions as stopping at the skin, while motivations deal with getting into practical relations with the environment. One popular idea derived from this distinction is that some people respond to frustration more viscerally and others more muscularly: this difference is called "anger-in" and "anger-out." In our culture, women are more prone to respond with anger-in while men are more prone to anger-out.

These divisions also parallel those made by Freud: primary processes fail to include reality testing (which depends on a double loop of attentional processing); reality testing defines secondary processes during which we seek to get into practical relations with the world we navigate. It is important to note that, for both James and Freud, assessing "what to do?" as well as assessing "what is it?" deal with *attention*. *Thus, assessing "what to do?" motivation, is a disposition, an attitude, not an action*. Interestingly, both in French and German "behavior" is called *comportment* and *verhaltung*—how one holds oneself. *In this sense, attending to "what is it?" also becomes an attitude.*

I received an award from the Society of Biological Psychiatry for showing that the upper basal ganglia (cau-date and putamen) organize and assess, the sensory input involved in "what to do?"—that these basal ganglia control more than the skeletal muscle systems of the body, as is ordinarily believed. The award was given for my demonstration that electrical stimulations of the basal ganglia alter receptive field properties in the visual system in both the thalamus and the cortex. In discussing my presentation of these results, Fred Mettler, professor of anatomy and neurology at Columbia University, had this to say at a conference there, during which he gave the introductory and final papers:

> *I don't think we should be deluded by the rather casual way that Karl presented this material. This is an elegant display of experimental techniques in an area which is extremely difficult to handle. I congratulate you, Karl. What he has shown you throws into relief the importance of two systems concerning which we have so far had only a few hints during the presentations of the two days. He has opened the way to a new symposium, dealing with the interconnections of the [basal ganglia] with the cortex on the one hand, and the [basal ganglia] with the thalamus, on the other. . . . The difference he has shown you . . . [is] what we may call the associational handling of sensory input. Without the [basal ganglia] the animal is quite unable to relate itself to its environment at a satisfactory level of self-maintenance. Without its cortex it is unable to relate itself accurately to its environment but it can still do it. The cat, maligned feline though it may be, is able to get along reasonably well without much cortex but if you add a sizable [basal ganglia] deficit to this, the animal looks at you with vacuous eyes and, in uncomprehending manner, will walk out of a third floor window with complete unconcern.*

Though these experiments were performed in the 1960s and 1970s, they have not as yet triggered an "orienting reaction" in the habitués of established neuroscience.

## Emotions as Hang-ups

Thus, the Four Fs are expressions of our basic dispositions to eat, to fight, to flee, to engage in sex. The experiments I've just described have shown that the behavioral expressions of these dispositions are rooted in the basal ganglia. The upper basal ganglia are involved in *starting and maintaining* these behaviors, while the limbic basal ganglia, especially the amygdala in its relation to the hypothalamic region, regulate satiety:

stopping eating and drinking, and placing social and territorial constraints on fighting and fleeing, and on sex. This raises a key question: What has "stopping" to do with emotion?

The answer to this question came from electrical stimulations of the medial hypothalamic region and of the amygdala in rats, cats, monkeys and humans. When the stimulation of these brain structures is mild, the animal or human becomes briefly alert. In humans, drowsiness or boredom are briefly interrupted—only to be quickly reinstated. Moderate stimulation results in greater arousal, an "opening up," with evidence of interest in the animal's surroundings. (In humans such stimulation results in a smile and even in flirting.) Medium-strength stimulation results in withdrawal and petulance. Strong stimulation produces panic in humans and what has been called "sham rage" in animals: the subject of the stimulation lashes out at whatever target is available. *Alerting, interest, approach, withdrawal, panic and emotional outburst are on a continuum that depends on the intensity of the stimulation!*

These results led me to talk about emotions as "hang-ups" because alerting, interest, withdrawal, panic and outbursts do not immediately involve *practical* relations with an animal's or a person's environment. The coping with pain and pleasure is performed "within the skin." As noted, William James defined emotion as stopping at the skin. When expressed, emotions *don't* get into *practical* relations with anything or anyone unless there is another person to "read" and to become influenced by the expression.

When we are no longer "hung up," we again become disposed to getting into practical relations with our environment; that is, we are motivated and our upper basal ganglia become involved.

# Conditioned Avoidance

Popular as well as scientific articles have proclaimed that the amygdala and hippocampus are "the centers in the brain for fear." Such pronouncements make some of us who are teaching feel exasperated. Of course there is a descriptive base for the popular assertions: Some scientists are interpreting the function of a particular brain system on the results of one experimental test or a group of related tests. When they find evidence, such as a freezing posture and increase of defecation in rats, they assume that the rat is “afraid.” Working with primates makes such assumptions more difficult to come by.

My monkeys, and even dogs, figured out what my experiments that aimed to test for “fear” were all about. In such experiments, a signal such as turning on a light indicated to the animal that it needs to jump out of its cage into an adjacent one to avoid a mildly unpleasant electrical current that would be applied to the bottom of the cage 4 seconds hence. Animals learn such a conditioned avoidance quickly. Monkeys showed me that they had become conditioned by jumping—and then by repeatedly reaching over and touching the electrified cage they had just jumped out of—that they knew what was going on. Knowing and emotionally fearing are not the same.

The dogs came to me with a Harvard graduate student who was to study the effects of removal of the amygdala in a “traumatic avoidance” experiment. In this experiment the dogs were to learn to avoid a noxious degree of electric current that was turned on some seconds after a gate dividing two compartments was lifted. In an initial experiment I lifted the gate without turning on any electric current—and the dogs jumped immediately to the other compartment. Was the “grass greener on the other side of the fence”? The student and I then substituted a flashing light for the “fence” as a signal that the dogs were to jump over a low barrier to reach the other compartment. The dogs learned to do this substitute for a ”traumatic” conditioning procedure in fewer than ten trials. (Of course, as was my policy for the laboratory, I never turned on any traumatic electric current whatever, at any time.) Dogs like to please and they quickly figured out what we wanted. In these experiments, both monkeys and dogs appeared pleased to have a chance to play and seemed cognitively challenged rather than afraid.

## A Story

How to choose the course of the “what is it?” and “what to do?” is beautifully illustrated by a story Robert Sternberg loves to tell, based on his dedication to Yale University, where he teaches and does research.

Two students, one from Yale and the other from Harvard, are hiking alone in the woods in Yellowstone Park when they come upon a bear. Both students are interested in bears, but have also heard that bears can be dangerous. The Harvard student panics. What to do? Climb a tree? Bears can climb trees. Run? Could the bear outrun us? Hide? The bear can see us. Then he noticed that his friend, the Yalie, had taken out his running shoes from his backpack, had sat down on a fallen log, and was lacing them up. "Why are you doing that? the Harvard student asked. "Don't you realize that you'll never outrun that bear whether you have track shoes on or no?" "I don't have to outrun him," replied the 'cortical' Yalie. "I only have to outrun *you*."

The bear was a novel experience for the students. Their visceral and autonomic systems most likely responded to the novelty. The intensity of the response depended on what they knew of bears in that habitat. The feelings of interest initiated by the sight of the bear were due not only to the visceral responses that were elicited; quickly the students' "what to do?" processes became involved. Further, at least one of the students entertains a "cortical" exercise, an episode in morbid humor, in *attitude*—or so the story goes. I can see them laughing, to the puzzlement of the bear, who wanders away from the scene.

## What Comes First

William James had suggested that the emotional components of attention *follow* our awareness of "what is it?" However, recent anatomical and physiological evidence has demonstrated that some sensory input (visual, tactile and auditory) actually reaches our amygdala *before* it reaches our brain's cortex. When this input is sensed, signals are sent, via the autonomic part of the brain's motor systems, to the viscera and adrenal gland. Thus visceral and endocrine activity is inaugurated on a "fast track" before cortical processing (the perception of the event) occurs.

Experiments have repeatedly shown that an event can have an effect when we do not recognize the content of the experience. The experiments consist of showing one hundred pictures to a person and then briefly showing five hundred pictures of which one hundred are the ones previously shown. People have no difficulty in identifying the one hundred as having been previously experienced—although they can't remember the content of these pictures. To experience a specific emotion, such as fear, we must be afraid of something, but the previously shown pictures evoked no recognition and therefore only a feeling of familiarity.

My colleagues and I had shown, in the experiments described above, that removal of the amygdala did not abolish the visceral and endocrine responses when the animals were exposed to a novel pattern. The amygdala were only a part of the limbic motor cortex that could convey the novel input. But much to our surprise, these responses persisted as the pattern was repeated: the responses did not habituate.

Habituation, familiarization was dependent on the presence of an intact amygdala able to process the visceral and endocrine responses. The amygdala were involved in processing the effects of body responses so that the novel pattern became familiar, a part of the subject's memory, a "neuronal model" of the experience.

In the absence of habituation, animals are physiologically aroused by anything and everything as if it were "novel"—the response activating visceral and endocrine reactions. Novelty, the unfamiliar, triggers a visceral/endocrine response. *Triggering of visceral and endocrine responses by novelty brings together the activation and visceral theories of emotion but in a most unexpected manner.* The rest of this chapter describes this unexpected relationship between visceral activation and emotion.

## What Is Novelty?

There is a great deal of confusion regarding the perception of novelty. In scientific circles, as well as in art and literature, much of this confusion stems from confounding novelty with something that scientists and engineers call "information." During a communication, we want to be sure of what is being communicated. I often don't quite get what another person is saying, especially on a telephone, so I ask that the message be repeated, which it is, perhaps in a slightly different form. My uncertainty is then reduced. In 1949, C. E. Shannon and W. Weaver, working at the Bell Telephone Laboratories, were able to measure the amount of *reduction* of "unsureness," the amount of uncertainty produced during a communication. This measure of the reduction in uncertainty became known *as a measure of information*. (In 1954, Gabor related this measure to his wavelet measure, the quantum of information, which describes the *minimum* uncertainty that can be attained during a communication.)

The experiencing of novelty is something rather different. During the early 1970s, G. Smets, at the University of Leuven, performed a definitive experiment that demonstrated the difference between information (in Shannon's sense) and novelty. Smets presented human subjects with a panel upon which he flashed displays of a variety of characters equated for difficulty in being told apart. The displays differed either in the number of items or in the arrangement of the items. The subjects had merely to note when a change in the display occurred. Smets measured the visceral responses of the human subjects much as we had done in our monkey studies. Changing the number of items in the display—demanding a change in the amount of information to be processed, in Shannon's terms — produced hardly any change in visceral responses. By contrast, *changing the arrangement of the items into novel configurations (without changing the number or the items themselves) evoked pronounced visceral reactions. Novelty is sensed as a change in pattern, a change in configuration, a change from the familiar.*

In presenting the results of Smets's experiments, this past year one of my students at Georgetown complained that she understood that novelty is different from information: But *how*? Her classmates agreed that they would like to know specifically what characterizes "novelty." I stewed on the problem for three weeks and on the morning of class, as I was waking up, the answer became obvious:

*Novelty actually increases the amount of uncertainty*. This increase is the opposite of the reduction of uncertainty that characterizes Shannon information. Novelty, not information, is the food of the novelist as indicated in the quotation that introduces this chapter.

Normally, we quickly habituate to a novel occur-rence when it is repeated. We form a representation that we use as a basis for responding or not responding, and how we respond. *This representation of what has become familiar constitutes an episode, which is punctuated by a "what is it?", an orienting reaction to an event that initiates another episode until another orienting reaction stops that episode and begins a novel one.* We can then, together with other episodes, weave together the complex that forms these episodes into a story, a *narrative*. Unless a particular episode becomes a part of our "personal narrative," we fail to remember it.

## Constraints

How then are episodes formed from the stream of our experience? The basic finding—that our stream of consciousness, the amount of attention we can ”pay,” is constrained—comes from knowing that the “what is it?” *stops* ongoing experience and behavior. Monkeys with their amygdala removed did not stop eating or drinking or fleeing or fighting or mounting in circumstances where and when the normal animals do. After I removed their amygdala, *the boundaries, the where and when, that define a sequence of experience or behavior before a change occurs, were gone. In the normal animal, as well as in us, those boundaries define an experienced episode.*

I removed the amygdala on young puppies, and we got the same result I had obtained in monkeys. The puppies who had their amygdala removed did not rush to eat, as did their intact control littermates, but once they began eating they went on and on, long after their littermates had become satiated and had left the food tray. When we tested monkeys who had had their amygdalas removed to see whether they ate more because they were “hungrier” than their unoperated controls (or their preoperative selves), we found that the monkeys who had had their amygdalas removed were actually less eager to eat at any moment (as measured by the amount eaten over a given time period or by their immediate reaction to the presentation of larger food portions), but once they began to eat, they would persist for much longer before quitting the eatery.

When we are in the grip of an intense feeling, such as love, anger, achievement or depression, it *feels* as if it will never end, and it pervades all that we are experiencing. But after a while, feelings change; a stop process has set a bound, a constraint, on the feeling. *Satiety constrains appetites; territoriality constrains sexuality; cognition constrains fleeing or fighting*.

A constraint, however, does not necessarily mean simply a diminution of intensity. Constraints (Latin: “with-tightening”) may, under specifiable circumstances, augment and/or prolong the intensity of a feeling. It’s like squeezing a tube of toothpaste: the greater the squeeze the more toothpaste comes out. Obsessive-compulsive experiences and behaviors, for instance, provide examples of constraints that increase intensity.

Constraints are provided for us by the operation of a hierarchical set of our neural systems, of which the amygdala and other basal ganglia are in an intermediary position. Beneath the basal ganglia lie the brain stem structures that enable appetitive and consummatory processes and those that lead to self-stimulation: the homeorhetic turning on and off of pleasures and pains. At the top of the hierarchy of brain structures that enable feelings and expressions of emotion and motivation is the cortex of the frontal lobes.

Labeling our feelings as fear, anger, hunger, thirst, love or lust depends on our ability to *identify* and appraise this environmental "what" or "who," and such identification depends on secondarily involving some of our other brain systems, which include the brain cortex.

The chapters hereafter deal with the importance of the cortex in enabling the fine grain of emotional and motivational feelings and expressions that permit us to weave such episodes into a complex, discerning narrative.

## The Middle Basal Ganglion

I have said nothing about the middle basal ganglion, the globus pallidus, because little is known. Clinically, malfunctions of the middle basal ganglion have been held responsible for Tourette's syndrome, the occurrence of tics that are sudden outbursts of uncontrollable movements or speech acts, often exclamations of obscenities. Fortunately, these embarrassing intrusions become less frequent as the person grows older. On the basis of this clinical evidence, one can venture the conjecture that the middle basal ganglion when functioning normally mediates, at a primitive level, the relation between an emotional hang-up and an attempt at a motivated "getting into practical relation with the environment."

Such mediation is provided at a higher level, that is, with more cortical participation, by hippocampal processing. The experiments in my laboratory as well as those of others, described in Chapter 15, show that the activity of the hippocampus accomplishes efficient mediation between emotions and motivations by processing the episode, the context, the familiar within which attended behavior is occurring.

## Epilepsy

Before the advent of EEGs, the diagnosis of temporal lobe epilepsy was difficult to make. I had a patient who had repeatedly been violent—indeed, he was wanted by the police. He turned himself in to the hospital and notified the police of his whereabouts. I debated with myself as to whether he did indeed have temporal lobe epilepsy or whether he was using the hospital as a way to diminish the possible severity of his punishment. The answer came late that night. The patient died in status epilepticus during a major seizure.

Fortunately, most patients with temporal lobe epilepsy do not become violent. On another occasion, decades later, I was teaching at Napa State Hospital in California every Friday afternoon. After my lecture, one of the students accompanied me to my car, and I wished her a happy weekend. She was sure to have one, she said: she was looking forward to a party the students and staff were having that evening. The following Friday, after my class, this young lady and several others were again accompanying me to my car. I asked her how she had enjoyed the prior weekend's party. She answered that unfortunately she'd missed it—she had had a headache and must have fallen asleep. The other girls immediately contradicted her: they said she'd been at the party all evening—had seemed a bit out of it, possibly the result of too much to drink. Such lapses in memory are characteristic of temporal lobe epilepsy. The young lady was diagnosed and medicated for her problem, which eliminated the seizures.

An oft-quoted set of experiments performed in the early 1960s by S. Schachter and J. E. Singer at Columbia University showed that experienced feelings can be divided into two separate categories: the feelings themselves and the labels we place on those feelings. These experiments were done with students who were given an exam. In one situation, many of the students (*who had been planted by the experimenter*) said how easy the questions were, turned in their exams early and also pointed out that this was an experiment and would not count on the students' records.

Another group of students was placed in the same situation, but these planted students moaned and groaned, one tore up the test and stomped out of the room, another feigned tears. Monitors said that the exam was given because the university had found out it had admitted too many students and needed to weed some out.

When asked after the exam how each group felt about it, and what their attitude was toward the experimenters, the expected answers were forthcoming: the "happy" group thought the exercise was a breeze; the "unhappy" group felt it was a travesty to be exposed to such a situation.

As part of the experiment, some of the students had been injected with saline solution and other students with adrenaline (as noted, the adrenal gland is controlled by the amygdala.) Analysis of the result showed that the adrenaline-injected students had markedly more intense reactions—both pleasant and "painful"—than did the saline group.

The label we give to a feeling that has been engendered is a function of the situation in which it is engendered; its intensity is a function of our body's physiology, in the case of this experiment, a function of chemistry, the injection of adrenaline that influenced the amygdala/ adrenal system.

## Understanding What I Found

The results of the experiments described in this chapter show that the "what is it?" response is just that. It is a capturing of attention, a stopping of an *episode* of ongoing processes, an alerting. Stimuli that stop ongoing behavior produce an increase in uncertainty, thus arousal, interest, approach, avoidance and panic. The "what is it?" reaction occurs when an experienced *event* is novel. Repetition of the event leads to familiarization. Familiarization establishes a representation of the experienced event.

Familiarization fails to occur in the absence of visceral responses. Visceral and endocrine responses are necessary to the *formation* of a representation of the event, a memory. *Emotional feelings result from the activation of a memory, not directly from a visceral input, as suggested in earlier theories*. We do not experience an emotion when we have a stomach-ache unless it conjures up memories of possible unpleasant visits to doctors or even surgery. Visceral and endocrine activation follows a mismatch between what is familiar and the novel input. If the mismatch to what is familiar to us is great, we will experience the *mismatch* as disturbing, even as panic. These reactions occur along a single dimension of intensity: electrical stimulation of the amygdala in humans and animals produces alerting, interest, engagement, retreat and panic. Emotions result from the processing of familiarity. Visceral reactions are essential in gaining familiarity, a form of memory.

Visceral/endocrine inputs, ordinarily called "drive stimuli," play a central role in organizing memory, the retrospective aspects of emotions and motivations. However, *the impact of these "drive" stimuli on the formation of the memory is shared by attention to the environmental context, Freud's caretaking person, within which the emotional and motivational feelings are occurring.*

Having completed several drafts of this chapter, it occurred to me that the results of my experiments have shown that *emotions serve as attractors; emotions are the prospective aspect of a hedonic (pleasure/pain) memory process* just as motives are in Freud's memory/motive theory. The action-based memory/motive process involves the upper basal ganglia (the caudate and the putamen). Freud did not know about the functions of the limbic basal ganglia—in fact, neither did I, nor did my teachers when I was in medical school and during my residencies. The familiarization/ emotional process parallels the readiness/motivational process and involves the limbic basal ganglia (the amygdala and accumbens). *Emotion is the attractor—the prospective, attentional, intentional, or thoughtful aspect of processing familiarity.* Typically, as the saying goes when plucking the petals of a daisy: we attempt to assess whether he loves me; he loves me not—or will she; won't she. It is the conscious or unconscious emotional possible *prospect* (maybe next time it'll work) that accounts for "hang-ups" and for repeatedly returning into less than satisfactory relationships.

Labeling our feelings as fear, anger, hunger, thirst, love or lust depends on our ability to *identify* and appraise this environmental "what" or "who," and such identification depends on secondarily involving some of our other brain systems, which include the brain cortex.

# In Summary

1. Motivations get us into practical relations with our environment. They are the proactive aspect of an action-based memory processes mediated by the upper basal ganglia: the caudate and the putamen.
2. Emotions stop at the skin. Emotions are hang-ups. They stop ongoing behavior. Emotions are based on attending to novelty which increases

our uncertainty. Thus, we alert to an unexpected occurrence. We may become interested in such an occurrence and become “stuck” with this interest. More often, we become bored, habituated. Habituation, familiarization occurs as the result of a change in hedonic memory processes initiated in the limbic basal ganglia. Familiarization depends on visceral activation. Emotions include the *prospective* aspects of this change in memory.

3. Electrical stimulation of the amygdala of animals and people has produced, in ascending order of the amount of stimulation (applied randomly), reactions that range from a) momentary to prolonged interest; b) to approaching conspecifics as in sexual mounting or flirting; c) to retreating from the environment; and d) to outbursts of panic which may lead to attack, labeled “sham rage.”
4. In short, although processing the content of an episode (the familiar) is highly specific, the response engendered varies along an intensive dimension reaching from interest to panic and rage.

# Chapter 14
## Values

Wherein I chart the brain processes that organize the manner in which we make choices.

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*Motives like to push us from the past; values try to draw us into the future.*

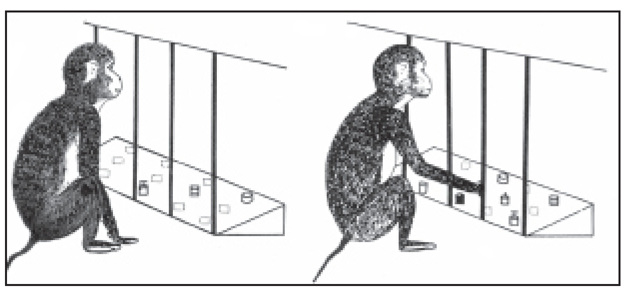
—George A. Miller, *Psychology: The Science of Mental Life,* 1962

*The empirical relations that determine the value of a piece of currency depend, in part, on the utility of that piece of currency for that particular individual. . . . Two interrelated classes of variables have been abstracted by economists to determine utility: demand and expectation; two similar classes have been delineated from the experiments reported here—each of the classes related to a distinct neural mechanism. [In addition] a still different neural mechanism has been delineated whereby preferences among values can be discriminated.*

—Karl H. Pribram, "On the Neurology of Values," *Proceedings of the 15th International Congress of Psychology,* 1957

## Preferences and Utilities

My claim in the previous chapter was that the amygdala and related systems are involved in familiarization, a form of memory, the prospective aspects of which form the basis of the intensities of our feelings and their expression. This claim raises the issue as to how familiarization is based on assessing and evaluating a situation in the world we navigate. An unexpected experimental result that we obtained in my laboratory addressed this issue. The experiment was a simple one, aiming to answer the question: Would a monkey who put everything in his mouth (and ate what was chewable) choose the edible foods before choosing the inedible objects when both were presented together on a tray? Before surgery, the monkeys had chosen mainly the edible objects; each monkey had shown a stable order in what had become familiar, that is, in what he preferred. Much to my surprise, after removal of the amygdala, *this order of familiar preferences remained undisturbed*—but the monkeys would now go on to take non-food objects and try to chew on them until all the objects were gone from the tray. Their "stop" process had become impaired.



*64. Object testing board*

In 1957, I presented the results of these and related experiments at the 16th International Congress of Psychology in Bonn, Germany. My text was set in terms of economic theory—especially as developed by the thesis of "expected utility" that had been proposed in 1953 by the mathematicians John von Neumann and O. Morgenstern. I had become interested in how we measure processes such as changes in temperature, and von Neumann and Morgenstern had an excellent exposition of the issue. Also in their book they talked about zero-sum games, a topic which became popular during the Cold War with the Soviet Union. It was during these literary explorations that my experimental results on preferences occurred, and

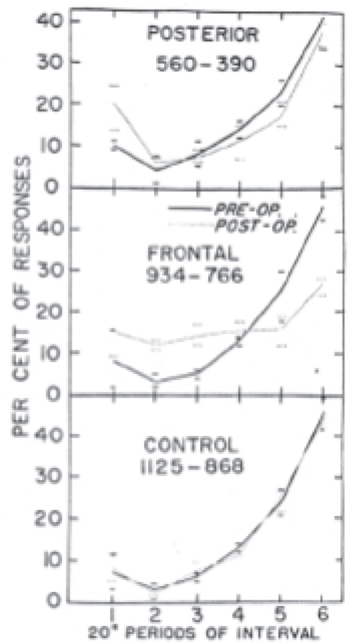
Von Neumann and Morgen-stern's depiction of the composition of utilities caught my attention. Wolfgang Köhler, friend and noted psychologist, came up to me after my initial presentation of these results and said, "Karl, you've inaugurated a totally new era in experimental psychology!"

I subsequently presented my findings at business schools and departments of economics from Berkeley to Geneva. During the 1960s and 1970s at Stanford, I often had more students from the Business School in my classes than from the psychology and biology departments. But despite this enthusiastic reception from the economic community, the inauguration of a new era in neuro-economics would have to wait a half-century for fulfillment.

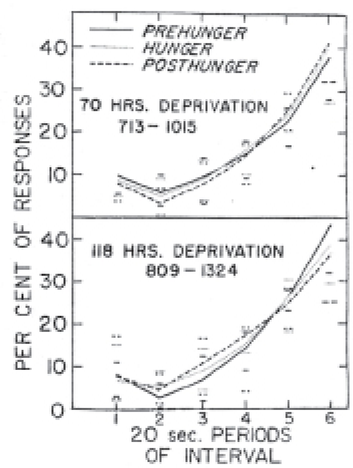
## Desirability and Duration

In my presentations to psychology, biology and economics students, and in publications thereafter, I suggested that the amygdala deals with the "desirability" of what is being chosen, while the frontal cortex is involved in "computing" the likelihood that the desired choice is available. Desirability is an intensive dimension that determines how much effort we are willing to expend in order to satisfy the desire. Desirability thus determines demand. Both my experiments with monkeys and my observations of humans revealed that the intensity of the desire for food, as measured by the amount of effort the person or animal would expend, is drastically *lowered* by amygdalectomy. The animals and patients ate more *not* because they were momentarily "hungrier" but because they failed to stop eating: *their stop (satiety) mechanism had become impaired*.

In the critical experiments demonstrating brain involvement in estimating the likelihood of achieving a desired outcome, I performed a "fixed interval experiment," so-called because it uses a "fixed interval schedule" for presentation of a peanut to a monkey. I scheduled a waiting period of two minutes between delivering each peanut to a place within the monkey's reach. During such a waiting period, animals and humans usually start out with very few responses (in this case, pressing a lever). The number of responses produced over a particular interval of time—that is, the rate of responding—increases gradually during the two minutes until just before the expected time of delivery of the peanut, when the number of responses reaches a maximum.




*65. Effect of removal of frontal cortex*

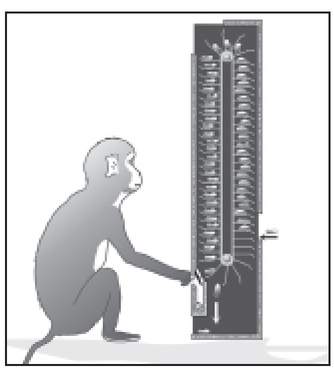



*66. Hunger deprivation has no effect.*

In running this experiment, I noticed that the signal on my desk that indicated when the peanut was being delivered was coming slightly earlier as time went on. When I investigated, I saw my monkey's hand reach out of the hole in his cage through which the peanuts were delivered, just seconds before the delivery period was up. The hand cleverly flicked the delivery apparatus (which was modeled after a refreshment bar delivery machine) into a premature delivery. The monkey timed his flicking so that the early delivery was hardly noticeable! I wondered how long this ruse had been going on and how many of my monkeys had been playing this game. Fortunately, the problem was easy to fix—a narrow tunnel was inserted between the hole in the cage and the peanut delivery machine.

The amount of studying done during a semester follows the same pattern, which is called a "scallop": at the beginning of each semester, students are apt to take their course work rather lightly, but as the semester goes forward, so does the amount of studying. In terms of economic theory, I interpreted the scallop to indicate that the estimation of the probability of being rewarded—the worry that we'll miss the boat by not studying, or miss the moment of the delivery of the peanut—"grows" exponentially over the interval.

Lowering or raising the amount of food available to, and eaten by, a monkey during the course of the experiment changes the *rate* at which he responds—that is the *number* of responses he makes during the two-minute interval between the delivery of each peanut—*but does not change the exponential shape of the scallop*: another one of those unexpected results. After removal of the frontal cortex, the rate of responding does not change, but the scallop disappears. Two of my four operated monkeys timed the expected delivery of the peanut so accurately that they needed only one response (the others made fewer than five) to obtain a peanut; the rest of the time they waited patiently or fiddled with the cage. This result demonstrated that, contrary to what most neuroscientists believe, clock timing is not disturbed by removals of the frontal cortex. Rather, it is a sense of duration: how long, and how structured an experienced interval seems.



*67. Peanut dispensor for monkey experiment*

In a classical (Pavlovian) conditioning situation, timing was so accurate in these monkeys that if we changed the interval between the conditional (signal) and unconditional (rewarding) stimulus, the animal failed to adjust to the new situation. The monkeys' estimation of duration had been fixed so narrowly that they missed opportunities that were just beyond the point of their fixation. As in the case of responding in the fixed-interval experiment, *their behavior had become fixated,* as is shown in human obsessive-compulsive disorders. The Greeks distinguished clock time, *kronos*, from a sense of duration, *kairos*. Our brains also make this distinction.

## Preferences

But the most surprising finding in this series of experiments was that the monkeys who had their amygdala removed showed no disruption of the order in which they chose the items presented to them. Their preferences were not disrupted. At the time when I was running my experiments, experimental psychologists were discovering a surprising fact: preferences were shown to depend on perceived differences arranged hierarchically.

In another set of experiments, my colleagues and I were showing that the removal of the temporal lobe cortex biased (led) the monkeys toward taking risks, whereas removal of the hippocampal system biased monkeys toward caution. Preferences were shown to be arranged hierarchically according to perceived risk: I prefer a Honda to a Cadillac; I prefer meat to vegetables; and vegetables to potatoes. Thus, I was able to relate my results on maintaining preferences after amygdalectomy to the monkeys' intact ability to perceive differences. *The amygdala are not involved with preferring meat to potatoes, as my experiments showed*.

By contrast, the intensive character of "desirability" is not arranged hierarchically, as was shown by Duncan Luce of the University of California at Irvine in his experiments on expectations. For instance, in his discussions with me, he noted that desirability, and therefore demand, changes dramatically, not according to some hierarchy, with changes in the weather (packing for a trip to a location that has a different climate is terribly difficult.) Desirability changes dramatically with familiarity (what is exciting initially has become boring) and with recent happenings as, for instance, when air travel became momentarily less desirable after the attack on the World Trade Center in New York— airlines earnings fell precipitously. It is practically impossible to rank (hierarchically) desirability and to try to do so can sometimes get one in trouble: Never, never attempt to charm your lover by ranking the desirability of his or her characteristics against someone else's. We either desire something or we don't, and that desire can change abruptly. Damage to the amygdala dramatically alters a person's or monkey's *desire* for food or any of the other Four Fs, not the ranking of preferences.

## "Concilience"—What It Means

Recently a comprehensive review paper published in *Science* has heralded a new approach to neuroscience: neuroeconomics. "Economics, psychology and neuroscience are converging today into a single, general theory of human behavior. This is the emerging field of neuroeconomics in which concilience, the accordance of two or more inductions drawn from different groups of phenomena, seems to be operating." (Glimcher and Rustichini, 2004)

The review presents evidence that when paradoxical choices are made (those choices that are unpredicted from the objective probabilities, the risks, for attaining success), certain parts of the brain become selectively activated (as recorded with fMRIs). These studies showed that, indeed, preferences, risks, involve the posterior cortex—a welcome substantiation of my earlier conjecture. But the review, though mentioning von Neumann and Morgenstern's theorem, fails to distinguish clearly between preferences and utilities, the important distinction that resulted directly and unexpectedly from my brain experiments.

The recent studies reviewed in *Science* confirmed many earlier ones that had shown that our frontal cortex becomes activated when the situation in which our choices are made is ambiguous. This finding helps explain the results, described earlier, that I had obtained in my fixed-interval and conditioning experiments: The frontal cortex allows us a flexibility, a flexibility that may permit us to "pick up an unexpected bargain" which would have been missed if our shopping (responding) had been inordinately "fixed" to what and where we had set our expectations.

Another recent confirmation of the way brain research can support von Neumann and Morgenstern's utility theory came from psychologist

Peter Shigzal's experiments using brain stimulation as an effective reward. He summarized his findings in a paper entitled "On the Neural Computation of Utility" in a book on *Well-Being: The Foundations of Hedonic Psychology*. Shigzal discerns three brain systems: "Perceptual processing determines the identity, location and physical properties of the goal object, [its order in a hierarchical system of preferences]; whereas . . . evaluative processing is used to assess what the goal is worth. A third processor . . . is concerned with when or how often the goal object is available."

The results of Shigzal's experiments are in accord with the earlier ones obtained in my laboratory and are another welcome confirmation. Contrary to practices in many other disciplines, the scientist working at the interface between brain, behavior and experience is most always relieved to find that his or her results hold up in other laboratories using other and newer techniques. Each experiment is so laborious to carry out and takes so many years to accomplish that one can never be sure of finding a "truth" that will hold up during his lifetime.

These recent explorations in neuroeconomics owe much to the work of psychologist Danny Kahneman of Princeton University whose extensive analyses of how choices are made received a Nobel Prize in economics in 2003. Kahneman set his explorations of how we make choices within the context of economic theory, explicitly contributing to our understanding of how our evaluations enable us to make choices, especially in ambiguous situations.

## Valuation

The important distinction I have made between preference and utility is highlighted by experiments performed by psychologists Douglas Lawrence and Leon Festinger in the early 1960s at Stanford. In these experiments, animals were taught to perform a task and then, once it had been learned, to continue to perform it. For example, a male rat must learn to choose between two alleys of a V-shaped maze. At the end of one of these alleys, which had been painted with horizontal stripes, is a female rat in estrus. The alleys with the female at the end are switched more or less randomly so that the placement of the female changes, but the striped alley always leads to her. The rat quickly catches on; he has developed a preference for the stripes because they always lead him to the female he desires.

Once the rat knows where to find the female, does he stop? No. He increases his speed of running the maze since he needs no more "information" (in scientific jargon, reducing his uncertainty) in order to make his choice of paths to reach her. But we can set a numerical "value" on running speed, on how fast the male runs down the alley. This value measures the level, the setpoint, of the male's desire for the female.

*Rewards (and deterrents) thus display two properties: they can provide information, that is, reduce uncertainty for the organism, or they can bias choices, place a value on their preferences.*

The experiments performed at Stanford by Festinger and Lawrence showed that the "laws" that govern our learning and those that govern our performance are different and are often mirror images of one another. The more often, and the more consistently, a reward is provided, the more rapid the learning. During performance, such consistency in reward risks catastrophe: when the reward ceases, so does the behavior, sometimes to the point that all behavior ceases and the animal starves. In human communities, such a situation arises during excommunication: a dependable source of gratification is suddenly withdrawn, sometimes leading to severe and incurable depression.

A slower and more inconsistent schedule of reward results in slower learning, but it assures that our behavior will endure during the performance phase of our experience. This is due to the buildup of the expectation that the current lack of reward may be temporary.

## The Reversal of Means and Ends

George Mace of the University of London pointed out that the "mirror image" effects shown between a learning situation and the one that exists during performance are examples of a more general means-ends reversal in patterns of experience. Reversals occur between 1) the acquisition of a pattern of behavior as, for instance, during learning, where our behavior is experienced as means to an end, and 2) the reversal of the pattern during performance, where our behavior becomes experienced as an end in itself. His example suggests that such means-ends reversals are ordinarily engendered by affluence:

*What happens when a man, or for that matter an animal, has no need to work for a living? . . . the simplest case is that of the domesticated cat—a paradigm of affluent living more extreme than that of the horse or cow. All basic needs of a domesticated cat are provided for almost before they are expressed. It is protected against danger and inclement weather. Its food is there before it is hungry or thirsty. What then does it do? How does it pass its time?*

*We might expect that having taken its food in a perfunctory way it would curl up on its cushion and sleep until faint internal stimulation gave some information of the need for another perfunctory meal. But no, it does not just sleep. It prowls the garden and woods killing young birds and mice. It enjoys life in its own way. The fact that life can be enjoyed, and is most enjoyed in the state of affluence, draws attention to the dramatic change that occurs in the working of the organic machinery at a certain stage. This is the reversal of the means-ends relation. In the state of nature the cat must kill to live. In the state of affluence it lives to kill. This happens to men. When men have no need to work for a living there are broadly only two things left to them to do. They can play and they can cultivate the arts.*

*In play the activity is often directed to attaining a pointless objective in a difficult way, as when a golfer, using curious instruments, guides a small ball into a not much larger hole from remote distances and in the face of obstructions deliberately designed to make the operation as difficult as may be. This involves the reversal of the means-ends relation. The 'end'—getting the ball into the hole—is set up as a means to a new end, the real end: the enjoyment of difficult activity for its own sake.*

## Addiction: A Tyranny of the Future

For years, learning theory was at center stage in the field of experimental psychology. Performance had long been a neglected stepchild. In my 1971 book *Languages of the Brain*, I called for a theory of performance and named it, tongue in cheek, "addictionance" theory because the process of addiction follows the very same rules as those that are in effect during performance.

Gambling hustlers and drug dealers know how to get someone addicted: the person is first readily provided with the substance which then, inconsistently, becomes harder and harder to obtain, either because opportunities become scarcer or because the price of the substance rises. At the addiction center in Louisville, Kentucky, an attempt was made to reverse this consequence by allowing a steady supply of substance to be readily available, and then to cut down the amount in regular, controlled stages rather than inconsistently. The technique was successful provided no other, more fundamental problems, such as incipient mental illness, had to be faced. For a while in England, addictive drugs could be had on prescription. While these laws were in effect, the criminal aspects that are produced by current law enforcement programs in the United States did not occur. Earlier, in the 1930s, we had a similar experience when Franklin Roosevelt ended prohibition of alcohol. The negative result of enforcement seems to be a hard lesson for governments to learn; the consequences of substance abuse overshadow a reasoned approach to it.

There are, of course, other factors that lead to addiction—factors such as genetic predisposition and cultural setting. But we do have a demonstration today of a situation in which addiction is avoided: when physicians prescribe morphine for long-lasting pain, the patients are readily weaned when the source of the pain is removed.

## In Summary

My surprising experimental results obtained in exploring the effects of amygdalectomy on expectation led to their interpretation in terms of economic theory. I had framed the results of experiments on the amygdala on changes in emotion and attention as indicating that emotions were based on familiarity, a memory process, and that the prospective aspects of familiarity controlled attention, and thus led to expectations. In turn, expectations were shown to be composed of three processes that were formed by three separate brain systems: preference, organized hierarchically, formed by the posterior systems of the brain; estimations of the probability of reward by the prefrontal systems of the brain; and desirability, an intensive dimension, formed by the amygdala (and related systems). This intensive dimension is non-hierarchical and ordinarily is bounded—a stop process—by the context within which it occurs. The composition of that context is the theme of the next chapter.

# Chapter 15
## Attitude

Wherein the several brain processes that help organize our feelings are brought into focus.

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*"A wise teacher once quoted Aristotle: 'The law is reason free from passion.' Well, no offense to Aristotle, but in my three years at Harvard I have come to find that passion is a key ingredient to the study and practice of law and life.*

*"It is with passion, courage of conviction, and strong sense of self that we take our next steps into the world, remembering that first impressions are not always correct. You must always have faith in people, and most importantly, you must always have faith in yourself."*

— Elle's commencement address in the movie *Legally Blonde*

# Efficiency: Remembering What Isn't

When I first began to remove the amygdala, I did so on one side at a time. Later, I was able to remove both amygdala in one operation. While the initial single-sided removal took from four to six hours, my most recent removals of both amygdala took forty minutes—twenty minutes per side. I have often stood in wonder when a skilled artisan such as a watchmaker, pianist or sculptor performs a task with an ease and rapidity that is almost unbelievable.

My experience shows that efficiency in performance develops by leaving out unnecessary movements. This chapter reviews the evidence that the Papez Circuit, the hippocampal-cingulate system, has a great deal to do with processing our experience and behavior efficiently, and how efficiency is accomplished.

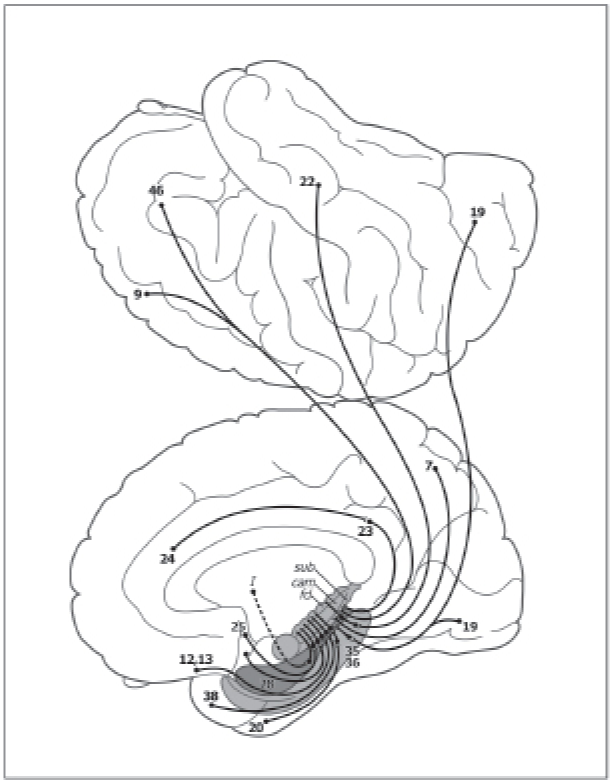
One of the Stanford graduate students in my class referred to the hippocampus as "the black hole of the neurosciences." It is certainly the case that more research is being done on the hippocampus than on any other part of the brain (except perhaps the visual cortex) without any consensus emerging as to what the function of the hippo-campus actually is. Part of the reason for the plethora of research is that hippocampal tissue lends itself readily to growth in a Petri dish: such neural tissue cultures are much easier to work with, chemically and electrically, than is tissue *in situ.* These studies clarify the function of the tissue that composes the hippocampus but does not discern its role in the brain's physiology or in the organism's behavior.

Another reason for the difficulty in defining the function of the hippocampus is that there is a marked difference between the hippocampus of a rat, the animal with which much of the research has been accomplished, and the hippocampus of a primate. In the primate, the upper part of the hippocampus has shriveled to a cord of tissue. The part of the hippocampus that is studied in rats is adjacent to, and receives fibers from, the part of the isocortex that receives an input from muscles and skin. Thus, removal of the hippocampus in rats changes their way of navigating the *shape* of their space.

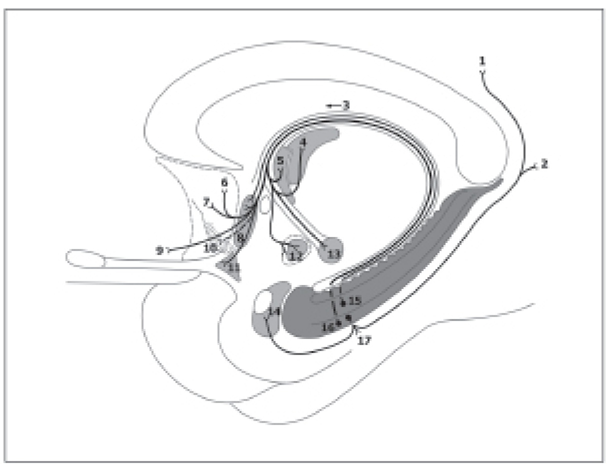
What remains of the hippocampus in primates is mainly the lower part. This part is adjacent to and receives most of its input from, the visual and auditory isocortex. Studies of the relationship of the hippocampus to behavior have therefore focused on the changes in their *patterns* of behavior beyond those used in navigating the shape of their space.

Just as in the case of research on the amygdala, almost all research on damage to the hippocampus in primates, including humans, has devolved on the finding of a very specific type of memory loss: *the memory of what is happening to the patient personally fails to become familiar*. Again it is memory, and familiarity, not the processing of information, or for that matter of emotion, that is involved.

Fortunately, I have found a way to work through the welter of data that are pouring into the "black hole" of hippocampal research: I can begin with the results of research that my colleagues and I performed in my laboratory. The most important of these was based on the observation that when we navigate our world, what surrounds the target of our navigating is as important as the target itself. When I steer my way through an opening in a wall (a door), I am not aware of the wall—unless there is an earthquake. I am familiar with the way rooms are constructed and, under ordinary circumstances, I need not heed, need not attend the familiar. The example of the earthquake shows, however, that when circumstances rearrange the walls, the "representation" of walls, the memory, the familiar has been there all along. The experiments we performed in my laboratory showed that the hippocampus is critically involved in "storing" that familiar representation.




*68. Afferents to Hippocampus*




*69. Efferents from Hippocampus*

However, the processing of what is familiar is different for the hippocampal system than for the amygdala system. A series of experiments in my laboratory demonstrated that while the amygdala is processing what is novel during habituation, the hippocampus is processing the context within which habituation is happening: the hippocampus is processing what is already familiar. In a learning task, when a monkey is choosing between a "plus" and a "zero" and choosing the "plus" is always rewarded irrespective of where it is placed, *the amygdala is processing choosing* the "plus," *the hippocampus is processing not- choosing* the "minus," the non-rewarded cue. This was a surprising result for our group until we realized that in order to walk through a door we must process the walls so as not to bump into them. Our experience with familiar walls has become, for the moment, ir-relevant, no longer "elevated" in attention. We no longer are interested in walls unless an earthquake occurs, in which instance our experience of the walls promptly dis-habituates and re-elevates into attention. The memory of walls and of the minus cue does not disappear during habituation and learning.

In another experiment, we recorded the electrical activity occurring in the hippocampus of monkeys trained to perform a "go no-go" task: on every other trial they were rewarded with a peanut for opening a box. On the intervening trials they had to refrain from opening the box. As expected, the electrical activity of the hippocampus was very different when recorded during the two responses.

We next trained the monkeys on a "go-right go-left" task in which each trial was rewarded: the monkeys had to choose between two boxes, one marked with a plus sign and the other with a square. The box with the square always had a peanut in it. The monkeys quickly learned the task and got themselves a peanut on every trial. Our surprise came when we analyzed the recordings of the electrical activity from the hippocampus: the electrical activity was identical to that obtained when the monkeys had had to refrain from opening the box in the previous task!!! When choosing between a plus and a square, the choice could be based on either a positive or a negative choice: "The plus always signifies a peanut" or "The square always signifies *no* peanut."

Actually, we showed that in ordinary circumstances, the monkeys attend, over the course of the experiment, both the "always a peanut" and "always no peanut" boxes when performing these tasks. But the brains of our monkeys sorted out which box is being attended, the amygdala responds to choose "always a peanut;" the hippocampus to choose "always no peanut."

In several other experiments we showed that the hippocampus is important in attending these "always no peanut" aspects of a task. For instance, the number of such “always no peanut” boxes on any given trial is important to monkeys whose hippocampus is intact, but not to monkeys whose hippocampus has been removed.

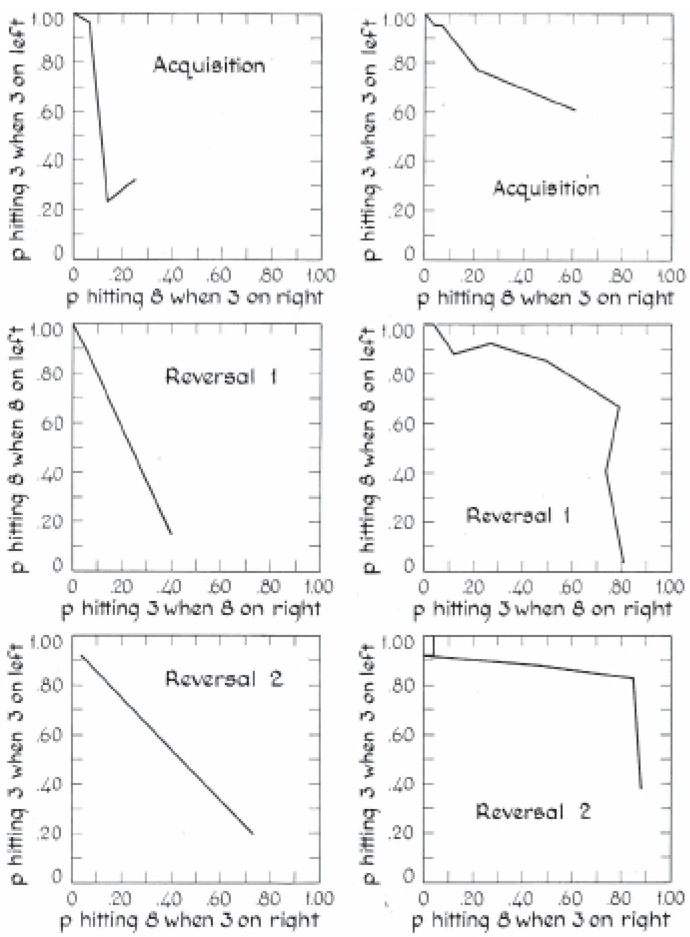
A slightly different but related effect of hippocampal removal was shown in a task in which the “always a peanut” was shifted from a panel with a plus sign to a panel with the square sign. The monkeys who had had their hippocampus removed learned that the shift had occurred as quickly as did the monkeys with their hippocampus intact—but once they had attained a 50% level of obtaining a peanut, they just continued at that level of performance. It seemed to me that these monkeys acted as if they were satisfied with being rewarded half the time without worrying or thinking. They were no longer motivated to do better. After a few weeks at this level of performance, all of a sudden the monkeys “snapped out of it” and went on to do as well as did the monkeys with their hippocampus intact. The slopes of achieving 50% and 90% were normal. But during the long period when they were at the 50% level, they seemed not to “want to exert the extra effort” to do better.

My interpretation was that at the 50% level of reward the new build-up of “not-choosing” had not proceeded sufficiently to counter the context of “not-choosing” from the pre-reversal stage of the experiment to kick the monkey into a more productive motivational phase. Support for this interpretation came from the finding that over progressive reversals the mid-plateau of 50% performance became progressively shorter.

Ordinarily, when we walk through doors, we do so efficiently; we don’t need to expend any effort scanning the walls for an exit. Come an earthquake, and we immediately make that effort by *“paying” attention* in order to find the safest possible place to shelter.

Experiments performed with normal rats have shown that, given several places where they might find food, they will quickly learn which places they have already found (and emptied of) food. They do not return to those now “always no food” *locations*. By contrast, rats who have had their hippocampus removed do return to such locations—over and over and over. In my laboratory, we obtained the same results with monkeys using different *non-spatial patterns* of “*reward*” and “*no reward:*” the monkeys who have had limbic system removals return—over and over and over—to the “no reward.”

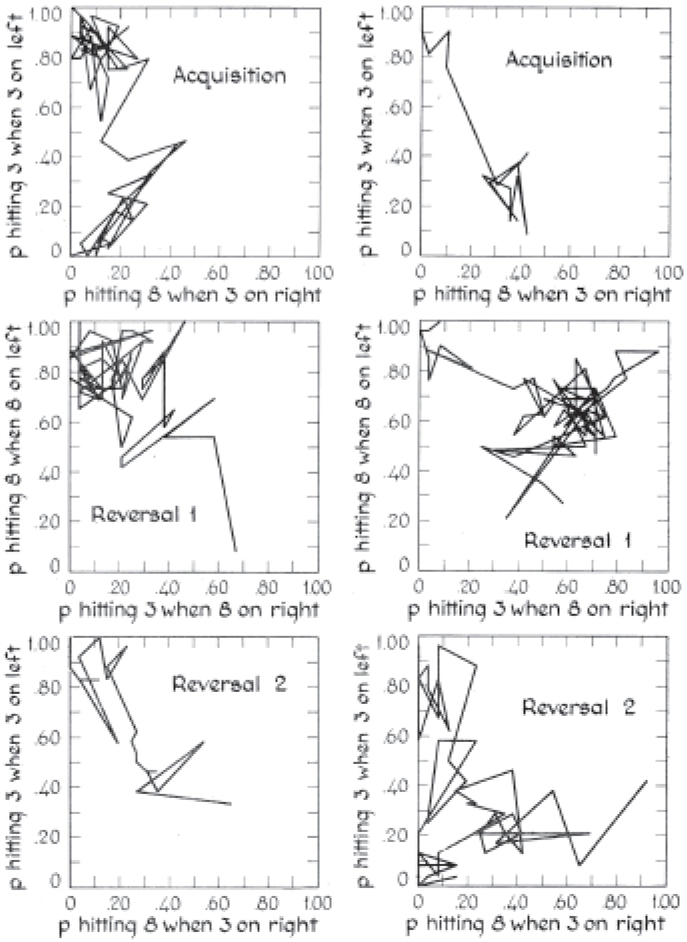
Much of the experimentation on the effects of hippocampal removals on behavior has focused on the spatial location of the unrewarded cues that animals continue to return to after surgery. As noted earlier, this is in large part due to the use of rats in most of the experiments and that the dorsal hippocampus is the site of the resections. The dorsal hippocampus is adjacent to, and connects primarily with, the somatic sensory and motor cortexes. In primates, the dorsal hippocampus has become vestigial (now it is a sliver of tissue called the "induseum griseum"). In primates the site of resection is the ventral hippocampus, as in my experiments. The ventral hippocampus is adjacent to, and connects primarily with, the visual and auditory cortex. Thus we can expect the function of the ventral hippocampus to be more "cognitive" than that of the dorsal hippocampus.




*70. Returns to No-Reward Cues: Control Subjects*

For decades, the results of these experiments on non-spatial cognitive deficits were ignored, but this is now changing: for instance, a study performed in David Gaffan's laboratory published in *The Journal of Neuroscience* (Wilson, Charles; Buckley, and Gaffan, November 2007) showed a similar impairment in learning randomly changing object discriminations.

A recent (1999) book by A. D. Redish, *Beyond the Cognitive Map: From Place Cells to Episodic Memory*, affords a comprehensive, critical and detailed review of the navigational functions of the hippocampus. The book comes to the conclusion that the hippocampus is important to our ability "to reset an internal coordinate system" and that this process is critical to both navigation and episodic memory. To me the book is a most worthwhile endeavor as it sets out an attractor network theory of how context resetting can occur. From my vantage, however, the context is not just a place code, as Redish and most of the scientific community continue to suggest; rather, the context is constructed by attending to any context that is "what isn't," what at the moment is *not* the focus of navigating our world.




*71. Returns to No-Reward Cues: After Brain Surgery*

# Holographic Aspects of Hippocampal Processing

In order for the animals with an intact hippocampus to "not respond" to where, or in which trials, there was "always no reward," a representation of prior experience has to be addressed. The nature of this representation has been well worked out: it is distributed. The cellular architecture of the hippocampus contains several webs rich in fine fibers that can serve as a holographic-like process. Some quotations from the 1970s of the work of John O'Keefe of the University of London, one of the most influential scientists working on the hippocampus, highlight the holographic nature of the hippocampal representation:

> *Attempts to gain an idea of the way in which an environment is represented in the hippocampus strongly suggest*

*the absence of any topographic isomorphism between the map and the environment. For example, cells recorded next to each other . . . are as likely to have their major fields in different parts of the environment as in neighboring parts. Furthermore, it appears that a small cluster of neighboring . . . cells would map, albeit crudely, the entire environment. This observation . . . suggests that each environment is represented many times over in the hippocampus, in a manner similar to a holographic plate. In both representation systems the effect of increasing the area of the storage which is activated is to increase the definition of the representation.*

*A second major similarity between the way information can be stored on a holographic plate and the way environments can be represented in the hippocampus is that the same hippocampal cell can participate in the representation of several environments . . . . There was no systematic relationship amongst the fields of the same neuron in the different environments. One can conclude that each hippocampal place cell can enter into the representation of a large number of environments, and conversely, that the representation of any given environment is dependent on the activity of a reasonably large group of neurons.*

*The third major similarity between the holo-graphic recording technique and the construction of environmental maps in the hippocampus is the use of interference patterns between sinusoidal waves to determine the pattern of activity in the recording substrate . . . . Pioneering work by Petsche, Stumpf and their colleagues (in Vienna) showed that the functions of [hippocampal cells] was to translate the amount of activity ascending from various brainstem nuclei into a frequency moduled code. [Hippocampal cells] fire in bursts, with a bursts frequency which varies from 4 to 12 Hertz. Increases in the strength of brainstem stimulation produced increases in the frequency of the bursts but not necessarily in the number of spikes within each burst.*

These important experimental results resolved any remaining reservations I had had in accepting the idea that there are "representations" of our experience "stored" in the brain. However, the representation in the brain has no resemblance to the experiences we encounter in navigating our world. Rather, the representations of our experience become to some extent distributed everywhere and every-when much as the patterns that become distributed in the holographic process. As in perception, the representations in the hippocampus must be *transformed* to be meaningful and of use in navigating our world. Transformations are carried out in the following manner:

## Hippocampal Processing Mediates Novelty and Readiness

There are two kinds of electrical rhythms that can be recorded from the hippocampus. (This is true of primates— where the distinction isn't obvious—as well as of non-primate species: in my laboratory we used computer analysis to tease the two rhythms apart.) One type of rhythm occurs when the animal alerts to a novel stimulus; the other occurs when the animal explores its environment. Most likely, when we alert to novelty (the "what is it?" experience) we encode that event into a holographic representation. When we then proceed to the "what to do?" phase, we engage the hippocampal rhythms that are activated when we explore our environment. In short, the "stop" process creates a holographic-like representation; in turn, the "go" process transforms that representation into a readiness to engage in practical space-time relations in navigating our world.

*The transformations that take place by virtue of hippo-campal function are, therefore, parallel to those that are performed in the perception/action systems. Hippocampal activity performs these transformations by bringing together and modulating the activities of the limbic basal ganglia "stop" processes with those of the upper basal ganglia "go" systems to assure the most efficient use of these processes.*

## Stress

Efficient processing of our experience depends on balanced metabolic processing. Stress has received bad press in this regard. True, excessively prolonged stress can be deleterious to our health and well-being. But without any stress we would probably eat and sleep most of our lives away. The hippocampus regulates the pituitary gland's secretion of steroids, the hormones secreted by the outer part, the cortex, of the adrenal gland. The adrenal gland is composed of this outer cortex and an inner core, which secretes adrenalin, also known as "epinephrine." This core secretion is regulated by the amygdala. *Thus the functional anatomy of the brain reflects the functional anatomy of the adrenal gland.*

*Adrenalin* mobilizes our stop processes, the "what is it?" attentional process. The amount of adrenalin secreted depends on what we experience: if being stopped in our tracks is frustrating, the intensity of our experience, abetted by adrenalin, increases.

When we activate our "go" processes, the processes that get us into practical relations with our environment, we are apt, in our society, to push ourselves to exhaustion. But more normally, hippocampal activity efficiently controls the *adrenal steroids* (which are closely related to the sex hormones) and ordinarily protects us from exhaustion. As every athlete knows, and those of us who have been administered steroids medically have experienced, they make us feel great. (Of interest in this context is the fact that the steroids and the endorphins are "cut" from adjacent portions of a very long protein molecule.)

The effect of hippocampal processing on *motivation* thus provides a context of specific patterns that are currently "irrelevant" but at the same time allows the motivation to be expressed along an intensive dimension: from feeling fine, feeling great, feeling stressed, feeling overwhelmed to feeling exhausted. Thus the hippocampus works for the expression of motivations much as does the amygdala for the expression of *emotions*.

# Bringing It All Together

In order to describe how brain processes are involved in organizing our emotions and motivations, we need to distinguish the names we use to talk about these processes. To begin with, in our common usage of the English language, we fail consistently to differentiate between emotions and feelings. I use the term "feelings" to describe both emotions and motivations, making an important distinction that goes back to William James. I have adopted James's definition: Emotions stop at the skin; motivations (which were called "instincts" in his day) get into *practical* relations with the organism's environment. Emotional feelings are generated when our bodies and brains cope *internally* with pain and pleasure. Motivational feelings concern our actions and the systems of the brain involved in starting and maintaining coping *behavior*. Feelings encompass our experiences both of emotion and of motivation: we feel happy, sad, or irritable; we feel gung ho to write a chapter, to plan dinner, to travel to a meeting.

Furthermore, in English we also use the word "feeling" to describe tactile (and visceral) sensations. Our language often embeds much wisdom. In close, intimate relationships we express our feelings of emotion, motivation and attitudes best by touching and hugging—using the tactile systems to communicate our emotional and motivational feelings.

As described in Chapter 10, tactile and visceral sensations take two routes from receptors to the brain. Disturbances of one route lead to loss of the ability to localize the origin of the sensation, say a pinprick, in the place where it occurs and the time when it happens. Disturbances of the other route result in changes in the hedonic—pleasant and enjoyable or unpleasant and painful—aspects of the sensation. The hedonic route organizes the brain processes that lead to our feelings of emotion and motivation. The difference between the localized processing of feeling and the hedonic processing of feelings can be stated simply: The knife feels sharp vs. I feel sharp today.

A chemical theory of the production of moods and emotions had guided the medical profession for centuries: the chemicals were called "humours," substances presumably secreted by certain viscera. In a much more sophisticated form, the chemical theory has emerged in what Candice Pert of Georgetown University has aptly named in her 1997 book *Molecules of Emotion: Why You Feel the Way You Feel*. The molecules include not only the simple transmitters adrenalin and acetyl-choline used by the autonomic nervous system, but also longer molecules, such as the catechol and indole (such as serotonin and histamine) brain amines. As noted above, the adrenal and sex steroids are involved in feeling great or feeling stressed. Even longer chain molecules such as oxytocin and vasopressin have been shown to regulate interpersonal attachments, including pair bonding.

A current version of William James's visceral theory of emotions needs, therefore, to become conjoined with the facts of chemical involvement in producing states of well-being and social engagement, and their disturbances. These ancient and modern insights led me to agree with Walter Cannon that much more is involved in generating emotions than the body's viscera. During the 1920s and 1930s, Walter Cannon had shown that the removal of those nerves conveying the signals from the viscera to the brain does not affect our experience or expression of emotion. Cannon further suggested that the thalamus, the last way station of input to the brain cortex, organizes our *emotional experience* and that the hypothalamic region, located just under the thalamus, controlled the *expression of emotions* such as fight and flight. My experiments showed that electrical stimulation not only of the hypothalamic but also of the limbic forebrain in human and animal subjects produces visceral changes and—as in Cannon's experiments—arousal, interest and even rage.

*However, sensing visceral or chemical activation per se is not what determines our experience or our expression of an emotion. Feeling an upset stomach or a cocaine rush are not emotions. Rather, the results of the experiments performed in my laboratory, based on Sokolov's experiments, demonstrated definitively that visceral activation is important not to the sensing of an emotion per se, but to habituation, to familiarization, the formation of an episode, certain type of memory and, furthermore, to attending to novelty, a change from the familiar.*

The question arose, therefore: What do the experiences of familiarization and novelty have to do with emotion? The answer came when I realized that I could think of emotion not solely as activating visceral and chemical processes but also as memory based. It was Freud's memory-motive concept that had attracted me to his *Project for a Scientific Psychology*. *Motivation considered within the context of processing the prospective aspect of memory (readiness) is a much richer concept, and accounts for a greater range of data than a purely drive (reduction or induction) based concept of motivation. Emotion considered within the context of processing the prospective aspect of memory (familiarity) is a much richer concept than one based solely on visceral and chemically based theories and can account for the surprising fact that* *practically all research into the psychophysiology of emotion has resulted in data pertaining to attention and memory.* The type of memory involved in motivation involves the upper basal ganglia (caudate and putamen). The type of memory involved in emotion enlists the limbic basal ganglia (amygdala and accumbens).

## Attitude

A comprehensive "attitude" theory of emotion and motivation can be constructed on the basis of the results of these experiments and the insights derived from them. Interestingly, Papez's intuitions regarding his views were on the mark: he published a chapter summarizing his anatomical circuit, and what he thought it signified, in 1969 in Nina Bull's book *The Attitude Theory of Emotion* (in which she included motivation).

As summarized in the current chapter, attitudes are formed from the prospective processing of memories: attitudes are motivational and emotional. The attitude theory is rooted in earlier ideas of William James and Sigmund Freud, and especially of James Papez and Nina Bull. Attitude became an important concept in social psychology during the 1920s. Floyd and Gordon Allport insisted, however, that attitudes were processes attributable to individual persons, processes that become of social consequence when the individuals interact. Gordon Allport once wrote a handwritten note to me suggesting that I was wasting my time working with monkeys; I should better devote myself to the study of human behavior. He would be surprised at what we have learned about "attitude" from those experiments on non-humans.

## The Structure of Attitudinal Patterns

When Floyd Allport retired, he came to Stanford and regularly attended my weekly lab meetings. He had more recently written his *Theories of Perception and the Concept of Structure* (1955). We ardently discussed his theory of event-structure, but the research on Gabor functions and patch holography was still in the future. It would be wonderful to be able to discuss the issues of event structure and attitude with Floyd and Gordon, given what we know today.

Our discussion might well look something like this: Attitudes are dispositional states that embody the experience of a person in compressed form. Attitudes are formed and reformed (reset) by structuring redundancy: each level of repetition is re-presented at the next level by a single symbol—and this process continues until all levels have been accounted for. In short, attitudes embody complexity—the construction of codes. Isocortical input becomes processed by the hippocampus, is then forwarded back to the isocortex via the basal ganglia (both upper and limbic) to be interleaved into ongoing processing.

# In Summary

The attitude theory of emotions and motivation, based on the experimental and theoretical advances reviewed above, can be summarized as follows.

1. Pain, as well as pleasure, is processed by homeorhetic systems that surround the ventricles of the brain.
2. Emotions and motivations are processes that cope with pain and pleasure.
3. Emotional processing stops at the skin. Motivational processing gets into practical relations with the world we navigate.
4. Emotions and motivations are based on a two-stage attentional mechanism: "what is it?" and "what to do?"
5. Emotional and motivational processing involves the basal ganglia of the forebrain. Emotional processing centers on the limbic basal ganglia: the amygdala and accumbens and related systems. Motivational processing centers on the upper basal ganglia: the caudate and the putamen.
6. The limbic basal ganglia are involved in familiarization, the processing of an attended stimulus into an episode, a memory. The process activates a visceral reaction. No visceral reaction, no familiarization; no episode, no memory.
7. Attention—"what is it?"—is captured by a change in the arrangement of a familiar pattern, that is, by a novel stimulus, an event. Novelty stops ongoing processes. Repetition begets habituation, that is, familiarization.
8. The intensity of a response to novelty varies from alerting, through interest, withdrawal, and panic, according to what aspect of the familiar is activated by the novel stimulus.

9. Three classical brain theories of emotion—the chemical, the visceral and the activational—are encompassed by the attitude theory. However, contrary to the visceral theory, visceral responses, our gut feelings, are critical in restructuring what is familiar, the restructuring of an episode, a memory: visceral activation is not per se the immediate source of an emotion.
10. Motivation involves the upper basal ganglia: the caudate and the putamen. The involvement of these structures is *not* limited to organizing postural readiness, but also includes attending, the control of sensory input.
11. The processing of the familiar utilizes the hippo-campus. The electrical activity in the hippocampus indicates that the familiar *becomes,* on repetition, the "always *not* the target," the seemingly "irrelevant" context in a situation.
12. Hippocampal activity provides efficiency to our processing of emotion and motivation. This is accomplished by eliminating attention to what is repetitively encountered. The processing becomes automatic (unconscious.) This entails encoding a hierarchical structure of redundancy. Thus, attitudes embody complexity; attitudes embody the processes that embody codes. In this way, hippo-campal processing efficiently brings together the response to novelty, the "stop" emotional process, with the "getting into practical relations with the world we navigate," the motivational "go" process. In short, hippocampal activity automatically determines the codes that form our *attitudes* as we navigate our world.

# Chapter 16
## The Organ of Civilization

Wherein I explore the executive processes of our brain.

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*The frontal "association areas" [of the brain], sometimes referred to as "the organ of civilization," are intimately connected with the limbic systems to form an internal core of the forebrain. This most forward portion of the primate frontal lobe appears to us to serve as a "working memory" where Plans can be retained temporarily when they are being formed, or transformed, or executed.*

—George Miller, Eugene Galanter and Karl H. Pribram, *Plans and the Structure of Behavior,* 1960

*There is some danger that the neuropsychologically oriented behavioral scientist may lose himself in the wealth of data and free ranging speculation that are now possible to him. But this danger is counterbalanced by the promise of a fresh view of mankind. Western thought has alternated between two views of man's relation to his universe. One view holds that he is an essentially passive organism shaped by the exigencies of his environment. The other [currently re-emerging] emphasizes his active role, manipulative and selective not only of artifacts but of sense data as well. The American neuropsychological contributions to behavioral science point to a resurgence of the dignity of man as a scientific as well as a political and humanistic tenet.*

—Karl H. Pribram, "Neuropsychology in America," in *The Behavioral Sciences Today*, 1963

## An Unexpected Finding

As I was moving from Stanford to Virginia in 1989, I was asked by the editors of the journal *Developmental Psychobiology* to mediate a controversy in the human brain electrical recording (EEG) literature. The controversy centered on whether or not brain electrical activity mirrored Piaget and Inhelder's decades-long observations that the development of cognitive processing occurs in distinct stages.

With my Stanford laboratory colleague Diane McGuinness, I had just published a paper entitled "Upstaging the Stage Model," in which we proposed that the distinctiveness of such stages comes about when a child is simultaneously learning many new skills and developing innate capacities. We also claimed that stages can be discerned in adults whenever they tackle a totally new set of problems. Such stages include a) an initial "hands-on" effort to get acquainted with the problem, b) a period of asserting control over the variety of factors involved, and c) a final stage of more or less skilled performance. In literary circles, these stages compose the initial part of what is called a "hermeneutical circle."

In my course on "Brain in the Context of Interpersonal Relations," which I've been teaching for half a century, I compare the Piaget stages with the stages of Freud's clinical theory and Harry Stack Sullivan's theory of interpersonal development. Most professional psychologists are shocked by the juxtaposition of these three "stage" theories, but I have come to this juxtaposition with authority: In the early 1960s, I happened to be in New York on the occasion of a lecture by Piaget at the William Allison White Psychoanalytic Institute. I was totally surprised when Piaget made the case that Freud's oral, anal and sexual "emotional/motivational" stages coincided with Piaget's own "cognitive" developmental stages. After the lecture, Piaget, Inhelder, his life-long associate, and I had dinner together. When I expressed my surprise, and noted that associating his own beautifully research-based theories with Freud's somewhat messy ones might be unwise, Piaget assured me that he was serious. (This was before my own explorations of Freud's *Project.*)

As a result of this exchange, I looked further into Freud's clinical theory and then added what I had learned from my colleague Gregory Bateson, and from the group at the Palo Alto Psychiatric Institute, with respect to Sullivan's interpersonal theory. Given my interest in form, especially form as pattern, I zeroed in on a critical point: Content may vary, but the patterns of development appear to be similar for both interpersonal (emotional/motivational) learning and for cognitive and skill learning—and these "stages" are not limited to childhood and puberty. The stages of our development are repeated whenever we tackle a totally new endeavor.

I now return to the invitation I received in 1989 from the journal *Developmental Neurobiology* to mediate the arguments regarding the occurrence of developmental "stages" in brain electrical (EEG) recordings. There is good anatomical evidence that the ages at which large tracts develop in the human brain are coincident with changes in brain electrical recordings. We can thus use the brain electrical recordings as indicators of brain maturation.

My first step was to enlist my colleague William Hudspeth, a psychologist and an expert in the analysis of human brain electrical activity, to help gather all the published data that might be relevant to settling the controversy as to whether there are Piagetian "stages'" recognizable in the EEG. We next looked at the time segment over which the recorded EEG had been used by various experimenters to determine a "stage." Some segments were as short as six months and others as long as two years. Hudspeth and I chose an age group confined to a one-year segment to bring the data into register. Within such an age group we had a uniform segment over which we could average the data from all the reports. That helped to eliminate some of the discrepancies.

But more important, the data from various laboratories around the world averaged their EEG samples over the entire skull. All my previous work had aimed at showing the differences between the behavioral processes to which different brain systems contributed. In our attempt to resolve the "stages" controversy, Hudspeth and I, therefore, divided the human EEG recordings that we had collected according to six locations across the skull.

These two maneuvers—using a standard time segment and dividing the recordings according to location on the skull—allowed us to show that the Piagetian stages were mirrored in the changes in *local* electrical recordings. We found that the distribution of patterns of maturation of the EEG across the skull were somewhat complex, but that in general these patterns supported a maturation stage model which loosely fit the

Piagetian stages. The editors of *Developmental Psychobiology* felt that the controversy had been resolved and published our findings.

As so often happens during experimental research, we also came up with an unexpected, surprising finding —that maturation of the EEG takes place during the late teenage years and that this maturation occurs in the frontal region of the head. We found that *there is a marked "growth spurt" over the most forward part of the frontal lobe between the ages of 17 and 21 years*. These are the years that kids go to college—and are sent off to fight our wars. Two decades after we published our results, the judiciary has taken note of our findings and other supportive evidence to debate whether late teenagers should be held responsible as adults for their behavior. What makes this part of our brains so important that the law should be concerned with its maturation? Why has this part of the brain been called the "organ of civilization"?

## The Key

The key to understanding the most anterior part of our frontal cortex —the part that is usually called pre-frontal—is that it lies anatomically between the classical (upper) and the limbic motor systems of our brain: between the cortical systems that modulate our motivations and those that modulate our emotions. The anterior frontal cortex is thus situated to be the arbiter of our brain's attitude systems. Thus the phrase "the organ of civilization" was born.

The relationship between the pre-frontal cortex and the limbic forebrain was unthought of when I first began my research. What was then known was that major changes in personality occur when the frontal part of the brain is injured. Famous cases were quoted repeatedly (and still are) such as that of a patient who had a crowbar shoved through the front part of his skull: he changed from a careful, good provider and stable friend to a carefree roustabout.

But what might the frontal forebrain contribute to the form that a person's personality takes? A few clues toward answering this question resulted from studies of patients and research with animals. Neurosurgeon Wilder Penfield's sister had developed a brain tumor in her frontal lobe and he removed it. Her main problem after the operation was getting a meal on the table in the correct sequence. Often the soup was forgotten until just before dessert—or served after dessert, Chinese style! Penfield's observations of his sister reminded me of psychologist John Stamm's mother rats, who, after removals of their cingulate cortex, could not organize the retrieval of their babies to get them into their nest: a mother would retrieve one of the pups only to take another out of the nest while retrieving a third—and so on, leaving a field of scattered, unsheltered pups, in her wake.

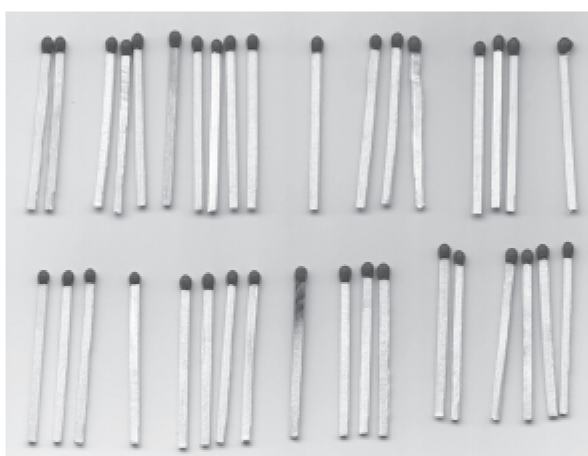
Non-human primates had been shown to fail a task that had originally been developed to test at what age human babies could find a piece of candy that had been hidden a few seconds or minutes before. For human babies, failure at this task depended on whether a distraction intervened between the hiding of the candy and the opportunity for finding it. For monkeys, hiding was ordinarily accomplished by lowering an opaque screen between the monkey and the hiding place. The screen was shown to be a distracter: if, instead of using the screen, the room was darkened, the animals always succeeded in finding the peanut. Distraction impacts our ability to remember just as it impacts our ability to perform a sequence of actions such as the retrieval of pups, or getting dinner on the table in proper sequence.

At the Yerkes Laboratory in Florida, I had operated on several chimpanzees, removing the anterior part of their frontal lobe, their prefrontal cortex. After surgery, when we tested these primates, they found ways to bridge the time that elapsed between showing them the hiding place of the reward and giving them the opportunity to find it. If the hiding place was on the left, the chimpanzee would pace along the left side of the fence that enclosed their living space; if the hiding place was on the right, the chimpanzee would pace the right side of the fence. Monkeys tested on this task might somersault to the left when a peanut is hidden on the left—and so on.

## The Topectomy Project

In Florida, during 1947, while I was simultaneously maintaining my practice in neurosurgery and performing experiments at the Yerkes Laboratory, I had the opportunity to visit New York and New Haven. Fred Mettler, professor of anatomy and neurology at Columbia University in New York, had set up a project in which different parts of the anterior part of the frontal lobe of humans were removed—rather than severing the entire lobe as in the lobotomy procedure. I had corresponded with Mettler because, in my Florida neurosurgical practice, I had been given the responsibility for a psychiatric ward of patients upon whom I was to perform frontal lobotomies. Being well trained as a surgeon, I decided to first test the patients myself to determine their preoperative capacities. I asked Karl Lashley for assistance in formulating a testing program, and he provided me with some tasks that might be useful to me, such as the "Porteus Maze," a paper-and- pencil maze through which the patient was to find the shortest path from the outside to its center.

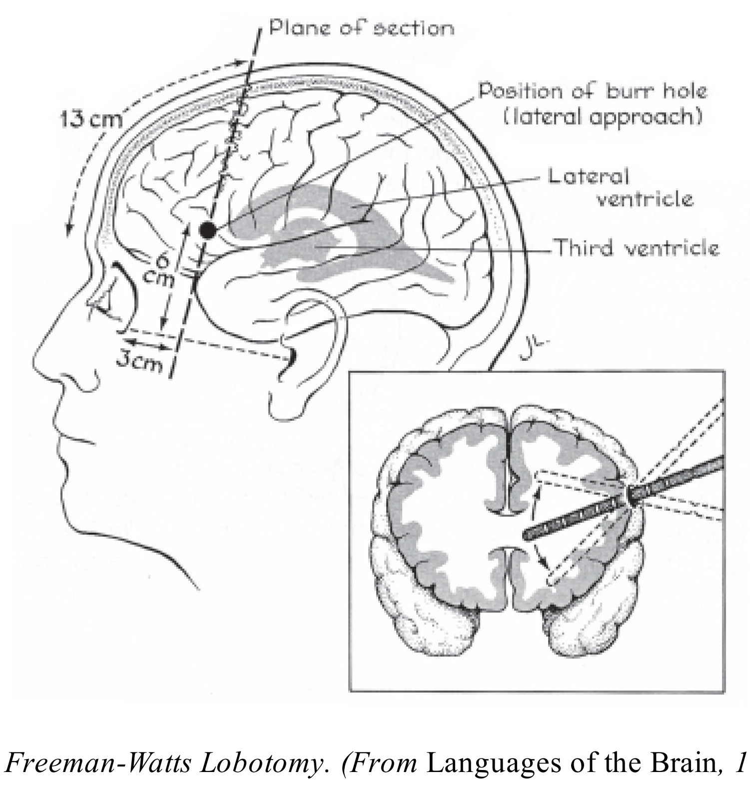
I also devised several tests of my own: for instance, a matchstick test in which the subject had to pick up every other match from an array in which the pattern is asymmetric. Patients with frontal lobe damage invariably had great difficulty in performing this task. Unfortunately, so did a few of the normal subjects (nurses) I tested, so that I could not publish any results. (I had not heard of statistics at that point in my career!) I also played checkers or chess with those patients whose problem was that they had intractable pain, to see if they could maintain concentration despite the pain. And of course I tested all subjects on delay tasks that had proven so helpful in our pre- and postoperative testing of non-human primates.



*72. Pick Up Every Other Match*

I soon noticed that most of these psychiatric patients improved remarkably, simply as a result of the attention I paid them during testing and just talking with them about their problems. James Lyerly, in whose neurosurgical office in Jacksonville, Florida, I was working, had devised a procedure for performing the lobotomy procedure through holes placed in the top of the skull—a much safer procedure than the standard Freeman-Watts approach through holes on the side of the skull, just above and behind the eyes, which Mettler and his colleague Rowland had shown was directly through "Broca's Area" in the brain. The Lyerly procedure allowed the surgeon to angle the cut forward, thereby avoiding areas of the frontal cortex closer to limbic structures.

On the basis of his experience and mine with the ward of psychiatric patients, Lyerly decided to perform lobotomies only on patients with intractable pain or those with severe obsessive-compulsive disorders. For such disorders, the procedure consistently provided relief with no observable side effects. The intractable pain patients I tested could now play checkers and chess, whereas before surgery, their pain had kept erupting, making it impossible for them to play. Now after the operation, when I asked about their pain, the patient's answer was "Yes, it is still there, just about as severe as before." But a few seconds later we were again playing the game.




*73. Freeman-Watts Lobotomy. (From* Languages of the Brain*, 1971)*

The people with obsessive-compulsive disorders were totally relieved of all symptoms: I remember a patient who walked around with her head bowed, looking only at the ground in front of her. She was afraid she would kill anyone she looked at. The day after her lobotomy, we played Ping-Pong—she was rather good at it.

While I was making these observations in our clinic, I was also testing chimpanzees on a task in which the animals became frustrated. The task consisted of giving the chimpanzee a choice between two well-marked objects, one of which was consistently rewarded. The procedure was easily mastered to perfection—until I suddenly ceased giving the expected reward. As a rule, the animals would withdraw from the task for a while and return a few minutes later to see if the reward was again available. I recorded the "frustration" of the animal by timing the minutes before the animal would return to the task.

This procedure worked well for me and showed that the duration of "frustration" was shortened in two chimpanzees in whom I had removed the cortex of the anterior portion of their frontal lobes. But I need to add that the procedure worked well except with one chimpanzee named Alpha. Alpha was given her name because she had been the first chimpanzee imported from Africa to become settled in the Yerkes Laboratories. Alpha was apparently not frustrated by my testing procedure. She would keep on testing, reward or no reward. This went on for ten days. On the eleventh, she did indeed stop testing when the reward failed to appear. I was timing the interruption when a load of feces came flying over the testing apparatus onto my head. I did not know how to rate Alpha's duration of frustration.

Sometime later, at Yale, I repeated the experiment with monkeys in whom I had removed the cingulate cortex. Their duration of frustration was dramatically shortened from what it had been before surgery.

The duration of frustration is a measure of the anticipation that the frustration will persist or be alleviated. Currently there are innumerable studies using brain-imaging techniques that show involvement of the cingulate cortex in a great variety of cognitive, motivational and emotional processes. I have not yet tried to collate the results of these studies to test the premise that "anticipation" is a common denominator that characterizes these processes.

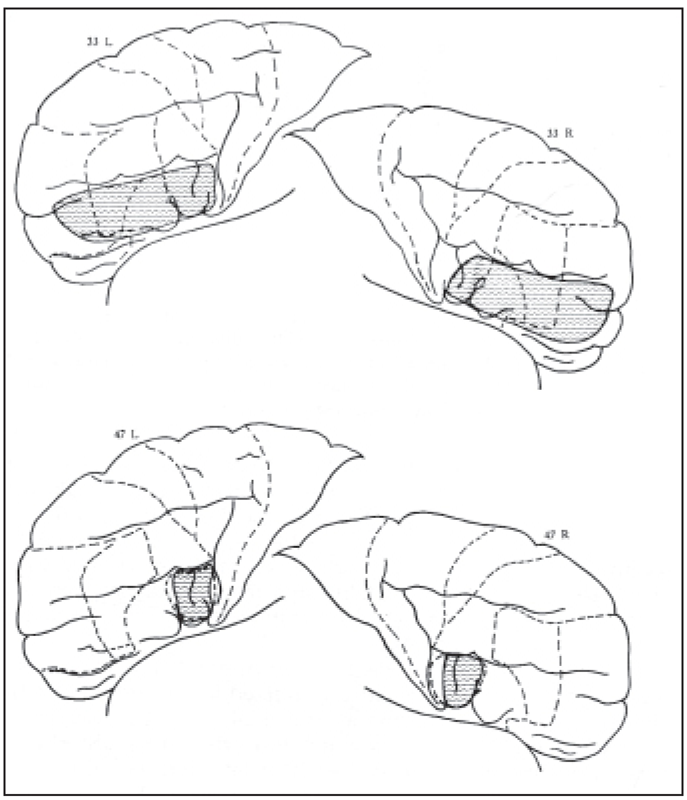
When I told Fred Mettler what I had been doing, he took me into his confidence. His topectomy project aimed to replace lobotomy with more restricted removals of cortex of the frontal lobes. There was a team composed of a surgeon, clinical psychologists, and a group of psychiatrists of various persuasions: Freudian, Jungian and eclectic. Only the surgeon knew which part of the cortex of each patient had been removed. Psychologists gave the same tests to all patients, both before and after surgery, at one-month and at six-month intervals. Their role was only to test the subjects; they did not know what psychiatric therapy was being given. The psychiatrists gave their best shot at therapy—knowing neither what the psychological tests were showing nor where the cortical removals had been made.

About a year after the project had gotten under way, Mettler invited me to New York, and we went over all the records together. After that, I made yearly visits; and later, once I had established a laboratory at Yale, some of his team came to work with me. What happened to the patients as a result of the Topectomy project came as a surprise to me and can be summarized as follows:

1. Whether the patient was rehabilitated into a socially competent and useful life depended to a great extent on the charisma of the psychiatrist.
2. The type of psychiatric therapy had no apparent effect on whether the patient was rehabilitated.
3. The location of the cortical removal did not determine whether the patient was rehabilitated.

An important byproduct of the study was produced when, in two decade-long catatonic mute patients, the neurosurgeon carefully removed the cortex of Broca's area without injuring any deeper structures such as the underlying white matter and the basal ganglia. Both patients spoke fluently after the operation—one within an hour, another within a day!!!

Larry Pool, professor of neurosurgery at Columbia University, the neurosurgeon who undertook this audacious procedure, did so because Mettler had found out that all of the Freeman-Watts lobotomies had been performed through Broca's area, and there had never been any consequent disturbance in speech. Broca had identified his "speech area" on the basis of four patients with massive middle cerebral artery strokes. The damage in all four cases impinged on the frontal lobe only slightly—but Broca was influenced by the then-current idea that the front part of the brain was involved in the generation of language. During the era of phrenology, the study of bumps on the head to predict personality traits, the front of the brain had been identified as allegedly dealing with speech because humans have high foreheads while primates with low foreheads (lowbrows) don't speak. To this day, neuroscientists and neurosurgeons still hold to the view that injury to the cortex of Broca's area produces Broca's aphasia. As I'll document in Chapter 22, I believe that injury to the basal ganglia underlying the cortex of Broca's area may be necessary to produce Broca's aphasia.




*74. Diagrams of frontal cortex of two patients showing bilateral removal of the inferior frontal convolution which contains (on the left) removal of Broca's area. No marked disturbances of speech resulted. One resection extends forward to include entire inferior frontal gyrus. (From Pool, et al., 1949)*

## John Fulton

As noted in Chapter 10, after visiting Mettler, I ventured to Yale to meet with John Fulton. Fulton was most gracious. I told him of my finding of cortical control of the autonomic nervous system, the work with Bucy. And I also stated that I did not obtain the results he had had in removing the frontal lobes of chimpanzees. The report he had made at the International Physiological Congress of those results had stimulated the Portuguese neurosurgeon Egaz Moniz to attempt frontal lobotomies ("leukotomies," they were called in England). Moniz was awarded the Nobel Prize for his groundbreaking work.

Fulton's important finding was that a neurotic, hard to handle and almost impossible to test chimpanzee became tractable and testable. There were two chimpanzees: Becky and Lucy. My frontally operated chimpanzees showed much more subtle changes: the duration of their frustration reactions were shortened, and they could perform the delay tasks by marking the side of reward by some intermediate "trick." Fulton pulled two large volumes of records from his shelves and said, "Take a look at these; I'll meet you here for lunch at noon."

The very carefully kept records were a revelation. During Becky's (the neurotic one's) surgery, a bevy of visitors watched: among them, Harvey Cushing, the father of neurosurgery in America. Because of this, or for whatever other reason, Becky developed a frontal lobe abscess which took months to become encapsulated (no antibiotics in those days) and heal. She was duly tested, having become tractable; years later, the massive remnant of the abscess was noted at autopsy. As I showed in later experiments, such irritating lesions are much more disruptive to behavior than simple removals of tissue. Lucy fared better and the results of her testing were identical with those I had obtained.

As noted in Chapter 10, over lunch, Fulton asked whether I had found out what I wanted. I answered, "Yes." He inquired no further but asked if I would like to come to Yale to work in his department. He had a grant from the Veterans Administration pending but needed a neurosurgeon to head it. All that I had been wishing for!—I have no idea how I got out of New Haven and back to Florida.

Four months later a telegram came: Could I start July 1st? Fulton was leaving for Europe and would like me on deck to take over. I had agreed to give a talk to the Duval County Medical Society, had to close my share of the neuro-surgical practice, and got Kao Liang Chow, a recently arrived graduate student from Harvard, to take over the testing of my animals (mostly almost finished) at the Yerkes Laboratory.

## The Yale Lobotomy Project

I was immediately put in charge of the monkey colony by Fulton and found that a considerable number of the animals had tuberculosis. I isolated these animals but had to keep them as long as they were being tested in the various projects under way. This responsibility did not endear me to my colleagues. I set up my laboratory, hiring out changes in the facilities as they were needed. Almost a year later I found out that there were "procedures" that one had to go through and that Yale would do the hiring. Fortunately, no one asked me to tear down what I had done. I rigged up a Yerkes testing apparatus much as the one I'd used in Florida. Yerkes came to visit—and suggested that I build something more substantial. (Yerkes and I became good friends later when I had taken over the directorship of the Florida laboratories from Lashley. He remarked that I was the best correspondent he'd had in the 20th century.)

Besides behavioral testing and neurosurgery, I was able to embark on chemical and electrical stimulations of what we now call the limbic systems. Results were obtained rapidly and I got them into publication in the *Journal of Neurophysiology,* which Fulton owned and edited. As noted in Chapter 10, within a year I had established the beginnings of evidence that the prefrontal cortex, including what we began to call the orbito-frontal cortex, worked as a higher-order controller of the limbic forebrain. I felt that the results of lobotomy in humans were due to this relationship. Fulton wanted me to write a book, but I felt that I didn't know enough.

Nevertheless, I was asked to consult all over the United States and in England. Also, I was asked to write an editorial on the lobotomy procedure that was published in 1950. As I tell my students today: "I was famous then." (Of course, I also tell them that the fame was as much due to the fact that a neurosurgeon would eschew practice and its attendant fabulous salary as to the research results that the project was harvesting.)

All did not go smoothly, however. The Veterans Administration rightly wanted some research done on human subjects, so a team was gathered by the Department of Psychiatry, a team that included therapists, psychologists, physiologists and chemists. The research was concentrated on two patients. At the end of a year, the patients had pretty much gotten well—as had my patients in Florida. What to do? All that investment in research, money and effort! The obvious answer, too bad; we've learned a lesson. To make a weeks-long story very short: The Department voted to go ahead; I resigned and went to my basement lab to continue the animal research.

There were other political issues to be handled. It was the time of the McCarthy investigations, among other unpleasant matters. I wrote Lashley for advice. It was given: "Make up your mind; do you want to do politics or do research?" Again, I went down to my basement laboratory.

A bit later John Fulton was relieved of his department chair and retired to the library he cherished. I found space in a nearby mental hospital, the Institute of Living, and built a laboratory (literally). I got the hospital to immediately reduce the number of lobotomies from two a week to two a month and gradually to two a year. The laboratory flourished as a research haven for PhD students who were awarded their degrees from Yale, Harvard, McGill, the University of California and Stanford (well before I moved there) on the basis of their research.

Meanwhile, I traveled around, trying to stem the tide of indiscriminate lobotomy. In these ventures I got to know Walter Freeman, Sr., and happened to arrive in his office the week he had disposed of the need for his neurosurgical partner by introducing an ice pick into the frontal lobes by way of the bony orbit that encases the eye. He no longer had to depend on a surgeon—or anesthetist: he delivered two electroconvulsive shocks to the patient so anesthesia became unnecessary. I saw the procedure done only once at one of Mettler's later research projects (sponsored by Columbia University and the Greystone Hospital). When Walter moved to California and was "operating" on children, I warned him that he might well soon land in jail if he didn't stop. He did stop.

Freeman was dedicated, and his career has to be looked at in the light of what was available and the conditions of mental hospitals at the time. Nonetheless, *without making a differential diagnosis*, wholesale "procedures"—which are now done with drugs, some of which were originally declared to be "substitutes for the ubiquitous use of lobotomies"—is poor medicine as well as unforgivable surgery.

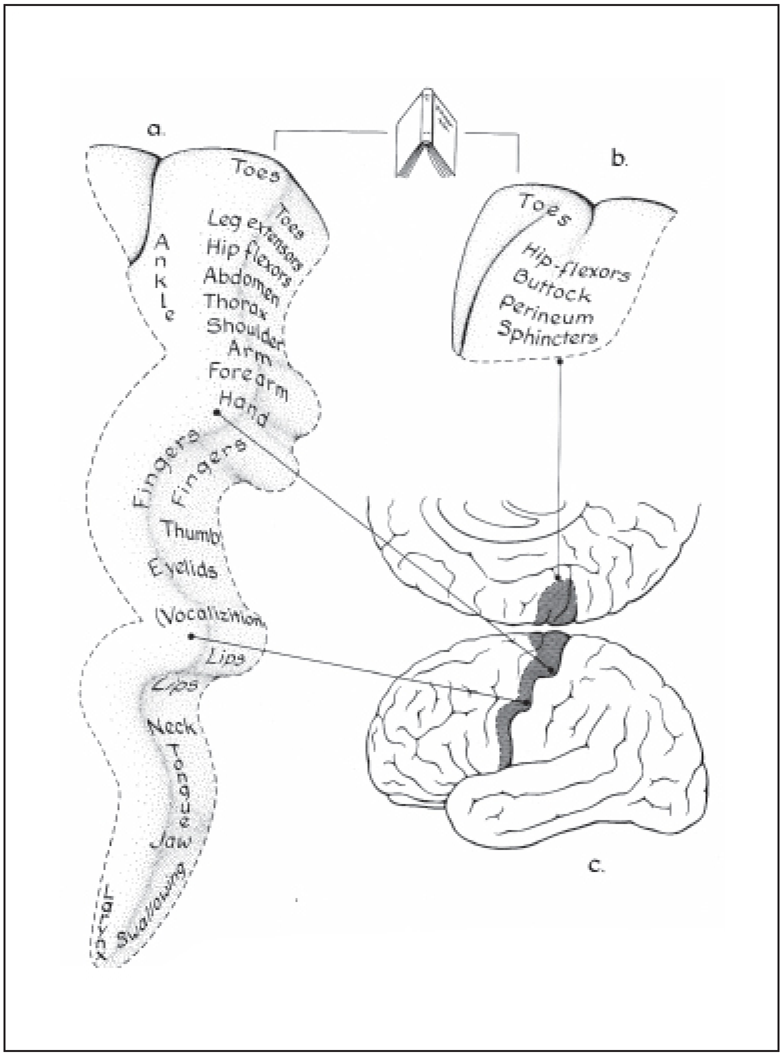
## What, When and How

Today, after a half-century of research, I know a lot more about the processes that become organized by the far frontal parts of the brain than I did during those early years at Yale. Anatomy is often a great help in defining the function of a brain system. The primate frontal lobe is highly conspicuous because the back end of our eyeballs is encased in bone. This encasement (called the "orbit") indents the brain so that its front part forms a "lobe" that occupies our foreheads and overhangs our eyes. Animals who lack this bony orbit don't have frontal lobes. If one is interested in comparing the brains of cats and dogs or rats and mice to those of primates, one needs to seek other criteria, such as the connections from the brain stem to the front part of their brains, to identify cortical systems that correspond to those of the primate frontal lobe.

Two different motor systems encircle the primate frontal lobe. The classical system, discussed in Chapter 8, was originally outlined by electrical stimulations of human brains during the Franco-Prussian War of the 1870– 1871. These stimulations produced movements of the body, including tongue, face, arms, hands, fingers, legs and feet. The classical system overlies and is densely connected to the upper basal ganglia. It is *shaped* according to its connections with the body—a distorted "homunculus." As described in Chapter 8, Malis, Kruger and I showed that this homunculus also receives a direct input from the body structures it "controls".

As noted in Chapter 10, working in John Fulton's department at Yale during the late 1940s, graduate, postdoctoral students and I outlined the second system—the mediobasal, limbic, motor cortex, by stimulations that produced primarily visceral and endocrine responses (although eye, head and body turning were occasionally observed). This mediobasal motor cortex covers the limbic basal ganglia.

The more anterior part of the frontal lobe, usually called pre-frontal, lies between these motor regions and contains the systems addressed in this chapter. I have identified three systems that compose this pre-frontal cortex on the basis of their anatomical connections to other parts of the brain and the effects on nonhuman primate and human behavior when they are injured.




*75. The Classical Motor Cortex. (From* Languages of the Brain*, 1971)*

The functions of these three systems can be characterized as regulating:

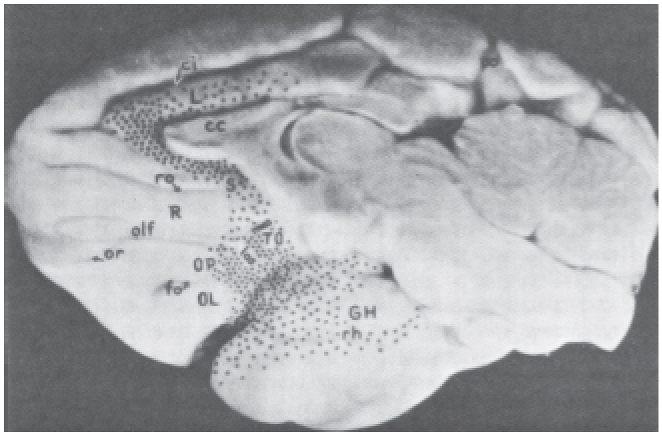
1. An extension of the limbic basal ganglia's "What is it?" by identifying the *proprieties* of behaving;
2. An extension of the upper basal ganglia's "what to do?" by working out the *practi-calities* of *how* to act; and
3. An extension of the Papez circuit's role in processing efficiency into effectiveness by assigning *priorities* as to when to act, the order in which an action is to proceed.

## Proprieties

The bottom (orbital) part of our pre-frontal cortex is densely connected with the amygdala in the temporal lobe. Given the role we have seen the amygdala to play in the processing of novelty and familiarization, it is not surprising that this frontal system deals with an extension of "what to do?": what we do in a novel situation depends on how familiar we are with the situation that provides the context within which we are processing the novelty.

I had to deal with a memorable patient who showed typical symptoms due to a tumor lying at the base of her frontal lobe (a meningioma of the cribiform plate through which the olfactory nerves enter the brain.) She was incontinent (peed in her bed), swore at the nurses, refused to help keep herself clean—in general she was a pretty horrible person. The tumor had grown slowly and was so large that it required three operations to remove it. The first thing the patient did after the third operation was to profusely apologize to the nurses for her earlier behavior. Shortly, her husband came up to me with tears in his eyes: "You have given me back the sweet girl I married." Notable about this patient's symptoms is that she recognized that her behavior was inappropriate, but was unable to correct herself.

On another occasion in Moscow, I argued with Alexander Romanovitch Luria for several weeks, demonstrating to him that a patient recognized that she was making errors, and was exasperated by failing simple tests we devised—but she could not carry out the appropriate series of actions. He argued that the patient was impaired in the motor aspects of carrying out sequences and that she was not aware of the impairment. One morning, Luria proclaimed that he had settled the matter: he had come in the previous evening and tested the patient to his satisfaction. I felt a moment of joy—until Luria made his next statement: "It all came out my way." His way was not my way, so when I went back to Stanford, Audrey Konow, a graduate student in my laboratory, and I repeated the experiments with several patients who clearly recognized their errors without being able to modify their behavior on the basis of that recognition, and published the results.




*76. The Limbic Motor Cortex. (From* Languages of the Brain*, 1971)*

Some years later, I published a paper reconciling Luria's and my views: What Luria had not taken into account is—as described in Chapter 8—that the motor systems of our frontal lobe deal with actions, the outcomes, the consequences of our behavior, not with those movements involved in producing our behavior. Luria's and my frontal lobe patients were impaired in their ability to manage actions, their "images of achievement"; they were not impaired in their ability to make the movements, the sequences of muscle contractions. They knew they were making errors, that they were off target, but they could not correct their behavior accordingly.

## Practicalities

Normal and optimal function of our brain and our body depends on *patterns*. Where there is no pattern, there is no function. All the major tracts in our brain and spinal cord are primarily inhibitory. The spinal cord is constantly discharging nerve impulses at a high rate of activity. This activity needs to be controlled by the brain's motor cortex (the pyramidal tract.) If it is not, all the muscles of the limbs contract simultaneously, so much so that the limbs contract into spastic "scissor-like" positions.

It is neural inhibition that produces *patterns*; patterns are what neural processing is all about. The middle part of the pre-frontal cortex, when acting normally, influences the motor systems of the frontal lobe, as well as the rest of the brain, through inhibition to allow one or another pattern to become effective in regulating behavior and experience.

Neural inhibition achieves the *patterned practicality* by which, when necessary, the pre-frontal cortex controls processing in the rest of the brain. This is the "how" of frontal lobe function.

# Priorities

The part of the pre-frontal cortex that organizes *when* we should do something, the order in which we choose to schedule our actions, lies on the upper inner surface of the lobe which is close to the cingulate cortex (which is part of the Papez hippocampal circuit). The hippocampal circuit helps to code what is being learned in such a way that it can be readily retrieved. Hippocampal activity aims at efficiency: As we get older, the hippocampus is one of the first brain structures to suffer deterioration. As a consequence, we have trouble quickly recalling names, remembering what to do next, even though we've rehearsed the names and the schedule.

But sometimes it is necessary to reorganize a schedule because of changed circumstances. Computer scientists distinguish between the efficiency of a program and its effectiveness: an efficient program conserves time and energy. But an efficient program may not be effective, so when it needs to be adjusted to new circumstances, the procedure of adjusting breaks down. Writing a paper or protocol efficiently confines it to as few paragraphs or pages as possible. But the efficiently written paragraphs may be incomprehensible to those who need to read and use them effectively. Running a shop or a laboratory efficiently often becomes difficult because the people involved feel unduly pushed under the time constraints imposed by management.

Sometimes a reshuffling of time slots and responsibilities leads to more effective arrangements and thus greater productivity. A simple example that I have experienced: I have my day planned to go to the bank, then to the auto shop, then to the psychology department, and so on. But the person I need to see at the bank hasn't arrived, so I have to return after I go to the auto shop. I had planned to return to the auto shop after I finished at the department, but the department discussions are taking longer than expected— so I dash out in the middle of it all to pick up my car. The ability to reshuffle priorities quickly can save us time and energy and money.

I became acquainted with the difference between efficiency and effectiveness during the early 1960s while assigning access to my laboratory computer. Priorities need to be assigned, and these priorities need to be shuffled in case of emergency or if the person whose money is keeping the facility going unexpectedly has a "great need." We used to call such programs "flexible noticing orders." The term "noticing order" calls attention to the experience aspect of controlling the program and thus our actions. The noticing order is the "image of achievement" that organizes action.

The upper part of our pre-frontal cortex, by virtue of its affinity to the cingulate-hippocampal circuit, has access to the patterning of our brain processes and adds needed flexibility to those processes. By the same token, the process of "what procedure to carry out when" is grossly disturbed when the pre-frontal cortex is severely injured. But injury is not the only cause of lack of flexibility. In patients who have obsessive-compulsive disorders, the frontal lobes appear to be working overtime, with a resulting limitation to their patterns of behavior similar to that which occurs when the lobe is damaged. This shows that our brain circuitry can malfunction either by virtue of an absence or excess of a process. Anesthesia provides an extreme example of both absence and excess: most anesthetics work by way of abolishing or minimizing brain activity. But the same result—"anesthesia"—can be produced with drugs that overstimulate the system, essentially producing an epileptic state that encompasses the entire cortex.

Conscious experience as well as unconscious processing depends on *patterns* of brain activity. To paraphrase the Clinton administration's dictum on economics, "It's pattern, stupid."

## Complexity

I wondered for many years how I might measure the rearrangement of patterns that is involved in the executive process, the rearrangements that rely on a flexible noticing order, a process that so dramatically produces the novelty that results in an orienting response. These rearrangements of patterns are distinctly different from rearrangements of shapes. A clue to what might be involved came from the experimental result that so clearly distinguished the cognitive behavior of monkeys in whom I had removed the prefrontal cortex of both hemispheres. Monkeys with such removals perform perfectly well on tasks in which they must choose between clearly marked stimuli, such as painted figures on the lids of boxes, when such stimuli are consistently rewarded. The ability to make such choices is dramatically impaired when the "association" cortex covering the back of the brain is removed.

By contrast, when the reward alternates between unmarked boxes, a monkey's ability to make choices is impaired by removals of the pre-frontal cortex, the amygdala and the cingulate gyrus. Such situations can be designated as alternating between "go right and go left," or between "go and no-go." (The ability to make choices among such alternations is not impaired when the cortex covering the back of the brain is removed.) During the 1970s, I performed a series of experiments showing that amygdala removals impair a monkey's ability to make choices when a variety of patterns of alternations in reward are made. I called such patterns portraying the structure of repetition "the structure of redundancy," in the technical language of information measurement theory.

I immediately realized that I had no measure, no precise idea of what I meant by "the structure of redundancy." William (Bill) Estes, one of the most eminent contributors to mathematical psychology, then at Stanford and later to become the William James Professor at Harvard, was editing my publication and asked me whether I really wanted to use the term "structure of redundancy." After some discussion, I said yes, and Estes agreed to let me have my way.

It was decades before I could take the next step in understanding what I really meant by the structure of redundancy. The answer came in a form familiar to us throughout this book: the mathematical field of inquiry that had developed during the 1980s called "non-linear" dynamics or "complexity theory." *Webster's Dictionary* notes that "complexity" is derived from the Latin *cum* (meaning "with," "together") and plicatum (weaving). Complexity is weaving something together. This "definition" provides an excellent metaphor for what I was looking for regarding the structure of redundancy but did not help me in discerning how to come up with a measure of complexity. I went to conferences and wrote papers expressing my disaffection.

The resolution to my quandary came through an unexpected route. During the 1990s, my colleagues and I were performing a series of experiments measuring brain electrical activity (EEGs) in humans performing a variety of tasks. I had wondered whether we could find out whether the EEG mirrored the changes in the difficulty (complexity?) of the tasks being performed. We tried several measures of complexity that had been developed in other laboratories but found that the EEG is produced by so many sources of variability that we could not tell whether the variability was random, produced by irrelevant changes (noise), or true complexity (whatever that meant.)

Paul Rapp, then of the Department of Neurology of Drexel University, had developed a data compression scheme that searches for a pattern that repeats itself within a string of symbols. We took the EEG recording, one electrode at a time, and followed that recording to where a change in pattern takes place. We mark the pattern with a letter. We go along the record until another change in pattern occurs. If the next pattern is the same as the earlier one, we mark it with the same cipher. If the pattern is different, we mark it with a different cipher. Next we go along the set of ciphers to see if there are any repetitions of sequences of ciphers, for instance, “xxy” in a series “abxxycdaxxyfghxxyabf.” In this series “ab” is also a repeat. Now we go to a new level, generating a new, shorter string by marking the “xxy” with the cipher “p” and the “ab” with “n.” For this example, the level of complexity is two; that is, no repeats of identical strings such as those composing “p” and “n” are found. By proceeding to analyze the brain electrical activity of 120 electrodes in this fashion, one electrode at a time, we observed many more levels than two where repetitions occurred in an electrode.

Algorithmic complexity thus turned out to be a useful measure of complexity—*and the measure of the structure of redundancy, of repetitions, that I had been searching for.* I’m glad I persuaded Bill Estes to let me retain “structure of redundancy” in the title of my paper so many decades earlier.

There is one more aspect to this story of the structure of redundancy: the measure of complexity and the amount of compression of our experience by our brain. In a recent discussion of my EEG results during a lecture, I was asked: How did we divide the series of changes in the recording when searching for repetitions? I answered, we didn’t divide them at all. But looking at the sequence of those EEG results on the blackboard, it became obvious that making divisions, “chunking” the sequence in various ways, would allow much greater flexibility in structuring our redundancy—that is, we could come up with many different ways of compressing our experience for future guidance in navigating our world. Chunking is a function of the pre-frontal cortex of the brain.

As an aside, Kitty Miller coined the term “chunking” while she, George Miller, and I were having dinner in Cambridge, Massachusetts. George and I were pondering the issue of how we make plans and the problem that our working memory is limited to about seven items, plus or minus two. How do we handle larger sequences as we do when we make and execute plans? We divide the task. We needed a name. Kitty volunteered: we were at the Chun King Restaurant; why not call dividing the task into chunks, “chunking?” The name stuck. Multiple ways of chunking provides a key to the practicality, the “how” of frontal lobe function.

## The How of Chunking

But what about the “how of the brain process” that allows chunking and re-chunking to occur? A possible explanation is rooted in work performed by Robert Thatcher of the University of Florida. Thatcher has shown that changes in the EEG are initiated at the thalamus. The EEG is constituted of a gradient of potential difference created in the brain cortex from surface to depth. These potential differences, these de-polarizations and hyper-polarizations occur in the small fibers of the cortex, the dendrites. The polarizations occur at various frequencies and, as I’ve noted earlier, their appearance in the EEG changes about 100 times per second. Thatcher’s contribution is his discovery that not only does the EEG change, but the relations within the EEG (the phase, the spectrum) also change rapidly. Scientists had already noted that changes in phase of the Alpha rhythm occurred with changes in visual input such as opening and closing our eyes. Thatcher measured the rapidity of the onset of changes in phase and found that they were too rapid to be carried out simultaneously over the entire expanse of the brain cortex: the origin of the onset of these changes was more likely in the thalamus. But once a phase has been set, the time taken for further changes in phase can be occurring across the cortex as demonstrated by simultaneous changes occurring in the cortical EEG.

This made sense because in several discussions with Thatcher I had also suggested to him that the thalamus might be involved in setting the phase relationship. In contrast, my suggestions centered on the projections from the thalamus to the limbic and prefrontal cortex.

The thalamic projections to the cortex take two very different forms. The thalamus is a three-dimensional structure; the cortex is essentially two-dimensional. Thus one dimension in the connectivity becomes "lost." In the 1950s, I had shown that for most of the thalamic projection the missing dimension is essentially outside to inside. By contrast, for the connections to the limbic and prefrontal cortex from the thalamus, the front to back dimension is absent. Thus, in primates, a file of cells in the thalamus projects to a "point" at the tip of the frontal cortex.

My suggestion, therefore, was that choosing a particular setting of a phase relationship is due *only* to the frontolimbic thalamus. My proposal has two advantages: it can account for the importance of attitudinal influences on cortical processing; and it can account for chunking and the changes in chunking that the prefrontal cortex is processing. These changes are accomplished by activating the reticular nucleus which surrounds the entire thalamus that, as Thatcher suggested, *initiates* the setting of the phase.

There is a relationship between a) my finding that removals of prefrontal and cingulate cortex alter the duration of an animal's or person's reaction to novelty and frustration and b) the finding that such removals of frontal cortex alter a person's ability to process complexity. Processing complexity, undoing a compressed, stored memory in the brain, takes a while. Pitfalls need to be avoided: solutions to a problem can be achieved which fall short of being the richest solution achievable.

Obsessive-compulsive behavior is such a solution to the problem of feeling anxious. Putting this into the terms of non-linear dynamics, in order to resolve a difficulty, we create landscape of the process in which there are valleys, that is, "wells" that the process can settle into—and the best solution, the richest valley, is never reached because the process becomes "stuck" in a shallower well. As noted so often, persons with frontal lobe injury appear to their families and friends as having become “shallow”—that is, less complex. Obsessive-compulsive behaviors demonstrate extreme lack of complexity, extreme shallowness.

# In Summary

The what, how, and when of pre-frontal cortex function comprise its role as the executive processor for the brain. Reflex behavior does not need executive control, nor does automatic behavior: As Sherrington put it, “The more reflex the behavior, the less mind accompanies it.” *Minding*, determining our attitudes, paying attention to sensory input, planning an action or thinking through a variety of compressed memory-based processes, recruits frontal lobe activity. Executive decisions search for *proprieties* on the basis of familiarity; decide what is *practical* by multiply chunking what is available; and assign *priorities* on the basis of current possibilities. In short, the pre-frontal cortex helps us organize the complexities that enrich our actions and our lives.

Very civilized.

# Chapter 17
## Here Be Dragons

Wherein I dispute a common misconception concerning the brain processes involved in organizing our massive aggressive behavior (such as warfare and ethnic cleansing) against one another.

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*Xerxes, we are told by the Historians, when from an eminence he viewed the numerous army with which he Intended to Invade Greece, wept bitterly, when he reflected that every man in that vast multitude, would be dead and rotten in less than one Century. This Thought moved the Tyrant, and drew tears from his eyes, when the prospect of the murders and butcheries he was preparing to commit, to gratify his vain ambition . . . This shows us that Tyrants, are not altogether Incapable of pity or compassion . . . These tender passions which Nature has planted in him, should be bent upon proper objects. We may hence Infer, that most, if not all Tyrants have been made so in great measure by Education, and, that parents and teachers, have very Industrially Contributed toward making monsters of them . . . .*

—An account of this story from Herodotus 7.46 appears in *The History of the Tuesday Club*

*The utility of all passions consists alone in their fortifying and perpetuating in the soul thoughts which it is good it should preserve, and which without that might easily be effaced from it. And again, all the harm which they can cause consists in the fact that they fortify and conserve those thoughts more than necessary, or they fortify and conserve others on which it is not good to dwell.*

—René Descartes, *Treatise on the Passions of the Soul,* 1649

*It appears that all of us share the same moral networks and systems, and we all respond in similar ways to similar issues. The only thing different, then, is not our behavior but our theories about why we respond the way we do. It seems to me that understanding that our theories are the source of all our conflicts would go a long way in helping people with different belief systems to get along.*

—Michael S. Gazzaniga, *The Ethical Brain,* 2005

It is time to pause to examine a tenet of what I have called "neuromythology" that, in my view, is severely harming our social existence. The tenet is that we have *inherited* "dragons" in the form of aggression and sexuality. According to that story, the dragons derive from our base ancestors and we must use our brain cortex to manage them. This version of the origins of human aggression has been latched on to by authors as famous as Carl Sagan and Arthur Koestler, lending to it credence and credibility when there is much evidence against it. My view and the evidence supporting it shows that our problems lie not with the "dragons" but with the very cortex that supposedly can tame them. My critique has several roots that I will develop one at a time.

## Aggression

During my years of research, we learned a good deal about aggressive behavior. Most helpful were my experiments that provided insights into the brain processes that are involved in organizing our attitudes, our emotions and motivations. During the 1970s, with a number of Russian and European colleagues, I helped found a "Society for the Study of Aggression," and I presented its first keynote address in Paris. My theme was that there are two very different modes of aggression: One mode is explosive, such as in the "sham rage" described in an earlier chapter, that results from maximal electrical stimulation of our hypothalamic or amygdala systems. Under ordinary circumstances, outside the laboratory, such behavior is elicited in us by intolerable frustration. Such explosive behavior is not clearly targeted, but rather it takes its toll on whomever or whatever happens to be around us. It is an *emotional outburst* that is not aimed at "getting into practical relations with the environment." In short, it is really not *motivated* in the sense that William James specified.

A totally different type of aggression is both motivated and "cool." A lioness is stalking a herd of gazelles. She stays out of sight, downwind, out of scent. She spots a laggard gazelle and waits until it is sufficiently separated from the herd before she pounces. She brings the gazelle's carcass to a safe place and allows her mate to have his meal. Then it is her turn to eat, and that of her cubs. From my male chauvinist standpoint, that is an ideal family arrangement! The lion doesn't even have to worry about the ethics of eating meat—he didn't do the killing. After eating, the lion is docile and out of the way so that the family can groom and nest. Leakey was fond of telling the story that on several occasions he had approached such a recently fed lion and was able to pet him. No hunger, no need for motivated aggression. No frustration, no emotional aggression.

Of course there are combinations of the emotional/ frustrated and motivated/calculated types of aggression, and these combinations can be especially dangerous as shown by "wars" among chimpanzees in which one tribe tries to annihilate another. The calculating political initiators of human motivated warfare often try to whip up emotional aggression against an "enemy"—but this must be limited by minimizing frustration and bonding among "friends" or the emotion becomes self-destructive on the battlefield.

# Male Aggression?

A standard image put forth by social anthropologists has been: male the hunter, female the gatherer. Under this image males must be more aggressive than females. But evidence has shown that hunting, especially in early societies, was a cooperative venture, while gathering berries, nuts or grains can be done in isolation, even if a whole group surrounds the picker.

It's true that the Y (male) chromosome, especially when doubled, has more often been shown to be present in criminal aggressive behavior than the X, the female chromosome. Likewise, high levels of testosterone, rather than of estrogen, have often been regarded as being the responsible agent in fomenting aggression. However, my experiments with monkeys have shown that under ordinary circumstances, genetic and endocrine factors *increase the intensity, not the frequency, of aggression*.

One of my failed experiments was a plan to put dogs and cats together, watch them become aggressive and then remove their amygdalas to observe the resulting taming. The animals were brought in from "death row" at the pound and housed in individual cages in my laboratory for a week. Some days prior to the contemplated surgery, I cleared a room, got cameras set, and enlisted enough people to pull the animals apart if things got out of hand. I let a half dozen dogs and a half dozen cats loose into the room. During the next hour, there was lots of sniffing and a bit of mounting. Then came nap time. There were cats snuggled up with dogs;

dogs with their “arms” around a cat: A really wonderful and impressive sight. There was no need to perform an amygdalectomy in order to produce taming. I surmised that a lot of the “aggression” we ordinarily see in domesticated animals starts with a chase which is often initiated simply by movement of the to-be “prey.”

On another occasion, after a severe winter snowstorm and during the succeeding cold spell, my family and I put out food in a line of dishes for birds and squirrels and other wildlife that might be hungry. Shortly we had a Noah’s Ark of animals all lined up next to each other—big birds, small birds, chipmunks and squirrels in a mixed array, side by side—with no one trying to usurp the contents of his neighbor’s dish. My comment at the time was: “It goes to show that if you give people enough to eat they behave agreeably.”

The lesson I took away from these observations is that the context in which the behavior is observed constrains behavior. Genetics, endocrines and the brain provide *possibilities*—potentials—but these possibilities become actualized according to the situation in which the organism finds itself. Social scientists are well aware that the situation within which behavior occurs is critical—but neither they, nor neuroscientists, nor practicing physicians are fully aware that this applies as well to how brain processes operate in a particular situation.

## The Triune Brain

After World War II, brain scientists began to study the brain from the inside out, peeling or coring it as if it were an onion, rather than slicing it from bottom up, floor-byfloor, skyscraper style. At Yale, my group working in John Fulton’s laboratory was using my neurosurgical experience to study the forebrain in this manner. With the results of my experiments in mind, my office-mate, Paul MacLean, came up with the idea that we really have three forebrains, one inside the next. With his gift for naming, he called the innermost brain “reptilian” because, according to the teachings of comparative neurology at the time, in reptiles this part of the brain, the basal ganglia, has become large and reptiles don’t have much else. The next layer he called “mammalian” because the anatomical structures that compose Broca’s *lobe limbique* are clearly evident in all mammals. The structures composing the limbic brain are the hippocampus which is archicortical (*archi*, “original”) and the cortex surrounding the amygdala, which is paleocortical (*paleo*, “old”). Finally, in primates including humans, MacLean noted that the “neocortex” dominates the forebrain.

MacLean made it clear that he had an agenda when he made these three divisions of the forebrain. His claim was that deep inside us there is an aggressive reptile that can become uncorked at the slightest provocation unless controlled by the flexibility provided by our more recently evolved brain structures. He asserted that the limbic forebrain’s functions provide this flexibility. The neocortex provides additional control based on reason.

MacLean’s theory hit a responsive chord in some scientific and many popular circles. *Homo sapiens sapiens*—the “wise one,” the cortical primate—is misled into aggressive action by the reptilian dragons buried deep in his ancestral brain. This makes for a great story, but MacLean’s story is an example of a myth gone wrong. It is wrong not only because its factual base is flawed, but also because it leads to wrong actions based on false premises.

Arthur Koestler, the novelist and popular science writer, spent some time at the Center for Advanced Studies in the Behavioral Sciences at Stanford during my tenure there. We held a joint seminar that was to lead to a joint publication, and we soon became lifelong friends. My daughter Cynthia was named after Koestler’s wife. One day, the Koestlers suddenly decided to leave California: it was never clear why. In departing, they left their Dalmatian coach hound, Tycho Brahe, with us as a gift to me and my family. (Tycho Brahe and Johannes Kepler gathered the data which Isaac Newton used to formulate his gravitational theory in the 17th century.)

On the way back to London, the Koestlers stopped in Washington, DC, for a visit with my colleague Paul Ma-cLean. A year or so later, Koestler published a book titled *The Ghost in the Machine*. I was unhappy. The first part of the book was based on the notes I had written up from the Stanford seminars that he and I had conducted together. The title of the book was borrowed, with no acknowledgment, from a phrase coined by the Oxford don Gilbert Ryle. The second half of the book was devoted to the triune brain. When I asked Arthur why he had not acknowledged Ryle, he replied that he had never believed in scientists’ addiction to dating discoveries and acknowledging sources. As for MacLean, Koestler was enthralled with his theories, which supported his own beliefs about the innate destructiveness of mankind. He told me, "If I had not met him [MacLean] I would have had to invent him."

Some years later, I visited the Koestlers at their home. They gave me autographed copies of all of Arthur's books, which he had stored in an adjacent barn, and we had a lovely tea together. Koestler had developed severe Parkinson-like symptoms that were controlled by medication, but this condition left him with only a few hours a day to work. I suggested that he and I publish a dialogue on how we viewed emotions—similar to the one that Eccles and Popper had done in their book *The Self and Its Brain*. Koestler was not sure whether he would be up to it, but we thought his wife Cynthia, who had edited and re-edited all of his works, could carry the major part of the burden of getting such a discourse down on paper. Six months later, the Koestlers jointly committed suicide: he did not want to go on in his condition, and she did not want to go on without him.

Subsequent books, such as Carl Sagan's *The Dragons of Eden,* have further popularized the idea that the oldest parts of our brain were reptilian, hence we are predestined to be combative and warlike. However, evidence in three categories indicates that exactly the contrary is true: the design of our brain's anatomy; the functions actually performed by those anatomical structures; and hard evidence from the laboratory concerning the effects on behavior of these functions. (For an excellent review of current comparative neuroscience see "One World, Many Minds" by Paul Patton, *Scientific American MIND,* December 2008/January 2009.)

The anatomical record shows that when fish landed and transformed into amphibians, a major change occurred in the basal forebrain (which in later evolutionary stages begets the basal ganglia) and the cerebellum. Tad-poles and frogs, salamanders and toads made the *really* big change—the change from living in a homogeneous aqueous environment to living in an inhomogeneous environment composed of storms and gravity. From the standpoint of the triune brain or Carl Sagan's *Dragons of Eden*, their disadvantage is that they are rarely aggressive or vicious and therefore don't fit the mold of "dragons inside us" that need to be vanquished by cortical humanity.

The basal forebrain, especially the basal ganglia, did become larger and more complex in reptiles, as MacLean claims, but the epitome of this development came in those reptiles that evolved and took to the air: birds. Parrots can be taught to identify objects with spoken words and even repeat strings of words from memory: the so-called "reptilian brain" par excellence. A visitor asked Richard Restak's grey parrot Toby, "Can you talk?" The parrot replied "Yes, I can. Can you fly?" Just as in the case of amphibians, the highly evolved reptiles known as birds just don't fit the mold of the "dragons"' presumably within us.

The limbic "old brain" is truly old. The oldest, the original cortex which grew into our hippocampus, is already present in sharks, one of the most ancient of the fishes. And recent research has shown that a part of the forebrain of birds is equivalent to mammals' hippocampus. Shouldn't sharks and birds share the characteristics of mammals, if those characteristics are due to the hippocampus as the triune brain theory proposes? The amygdala, another part of the limbic system, is not quite so ancestral as the hippo-campus, but is, as detailed in the previous chapters, one of the basal ganglia. But the basal ganglia, in the triune brain theory, characterize reptiles, not mammals!

In primates, including humans, the limbic allocortex surrounding the amygdala and hippocampus has accrued neo-cortical additions. These evolutionary changes have enabled us to experience and express complex emotional and motivational attitudes. In this respect, despite the anatomical misconceptions, the triune brain theory is correct.

In my view, the most glaring error in the triune brain theory concerns its conception of the functions of our brain cortex in the control of aggression, an error that is unfortunately shared by many throughout the brain sciences, psychology, and the humanities. The *error* is that our aggression, especially as it is expressed in warfare, is generated by the evolutionary older parts of our brains and that control of aggression must be exercised by our cortex over these older brain systems.

Bluntly stated, the *correct* proposition, based on evidence from both biological and social observation and experiment, ought to be: *the expression of aggression (and sex) in humans is related to our cerebral cortex. The refinement and duration of agressive experience and behavior expressed in humans is a function of the evolutionary later-developed outer "shell" of the brain rather than of processes organized by the core parts of our brain.* In short, *no animal lacking this highly developed cortex* *would distinguish between Roman Catholics and Orthodox Catholics and carry out "ethnic cleansing" accordingly*.

I'll come back to the topic of aggression later in the chapter. But first I want to show, using a less emotionally charged topic, that the same error is made in attributing the organization of human sexual behavior more to core-brain than to cortical processing.

## Sex and the Brain

The fallacy regarding the brain process that presumably generates aggression is also commonly held for the brain processes that organize sexual behavior. Some of the evidence for questioning the common view was presented in Chapter 11 in describing the experiments undertaken under the heading of the Four Fs. The conclusion reached in that chapter was that the apparent increase in sexual behavior that follows amygdalectomy is produced by a dissolution of the normal animal's territorial constraint on his behavior, his "stop" process, rather than by an increase in the amount of sex hormone circulating in his blood.

My colleague at Yale and subsequently at the University of California at Berkeley, Frank Beach, the experimental psychologist who devoted his life to understanding sexual behavior, asked me to look at the brains of cats that had been operated on by someone else. He had studied the sexual behavior of the cats and found that the females didn't want sex, even when their hormones signaled that they ought to be in heat. Beach wondered which part of the limbic brain had been invaded to produce such an oddity. The results of my anatomical examination were even odder than was the cats' behavior: I discovered in each brain that only the cortex had been removed! This was surprising: Why would removal of the cortex reduce sexual behavior in an animal whose hormone systems were still intact? All the female cat has to do to consummate the sexual act is stick up her rear end, a maneuver that could readily be accomplished by an animal with an intact "reptilian brain." I would have expected some effect of the cortical removal in male cats, who have a much more complex ritual and postural behavior to succeed in sexual mounting.

In a different experiment, I collaborated with Richard Whalen of the University of California at Irvine to find out if, perhaps, removals of the amygdala would have an effect on cats' sexual behavior. Whalen had a group of male cats he had been studying for years. He had completed these studies, so he and I planned to see whether the cats' sexual behavior would change after amygdalectomy. We chose some virgin females as targets for the males' sexual advances; virgin female cats have to be courted *very* patiently before they will give up their virginity. Once more we were in for a surprise: the amygdalectomized male cats were patient, skilled and successful in their courting. These old rogues had honed their intact brain cortex, which they now used successfully in the current situation. I had planned to present the results of this experiment in a talk at an upcoming conference on sexual behavior and was left empty-handed.

On the basis of these and the other studies previously described, I have concluded that the brain cortex has a great deal to do with the execution of the skills involved in both sexual and aggressive behavior, and that these skills include "wanting" sex or "entertaining aggression."

Many years ago, while I was on a somewhat delayed honeymoon, my wife and I met another couple, also on their honeymoon. They were lovely people and fun to be with, but on the second day the young man, who had chosen to be a minister, came to me in confidence. As I was a physician, perhaps I could help. His wife totally refused to have sex. He was completely surprised. I talked to this very beautiful young lady: she was as surprised as we were; after all, she had married a minister because she assumed he would be too holy to want sex!

Hormones? Limbic forebrain? Only the brain's cortex could be involved in surmising—or hoping— that ministers, like Catholic priests, might forgo a sexual relationship.

What is true of the critical role our cortex plays in sexual mating is true also for aggression. As I described earlier, aggression comes in two very different basic forms: emotional outbursts and motivated "cool" planning. We sometimes go to war or become terrorists because we are frustrated and angry. We sometimes go to war because of territoriality: "This is our turf, stay out." These forms of aggression do involve the amygdala and its relationship with other subcortical parts of the brain such as the hypothalamic region. They are reactive, defensive, and are expressed toward anyone who happens to be in the way.

But some of our most vicious and prolonged wars have been "predatory." They are fought on behalf of ideologies that only cortical sapiens sapiens could concoct—within economics: communism vs.

fascism; within Islam: Sunni vs. Shia; between Christianity and Islam; between Islam and Hinduism; within Christianity: Catholic vs. Protestant. Aggressors hope to "convert" or "eat up" the infidel. And all who wage war must have the lioness's skill if they are to succeed. These are our "dragons," but they are not buried deep within us; they are due to ever more polished refinements of our attitudes, made possible by our cortex and embodied in our cultural constraints.

## A "Sinister" Confirmation

There is a relationship between left-handedness (*sinister* is Latin for "left") and warfare. A study of traditional cultures found that the proportion of left-handers—that is, they preferentially use the cortex of their right hemispheres—is correlated with its homicide rate. For instance, violence, raiding and warfare are central to Yanomamo culture of Brazil. The murder rate among this society is 4 per 1,000 inhabitants per year (0.4% compared with 0.068% in New York City). Left-handers comprise 22.6% of the population. In contrast, Dioula-speaking people in West Africa are virtual pacifists. There are only 0.013 murders per 1,000 inhabitants (that is, 0.0013 %) among them and only 3.4% of the population is left-handed.

The study (reviewed in *The Economist*, Dec. 11, 2004) notes that individual left-handers are not more aggressive than right-handers. What appears to be the case is that left-handers have an advantage in hand-to-hand conflict because right-handers are not used to combat with the few left-handers they engage. This is true even today in sports like tennis and baseball. Thus the left-handers often score more victories and this becomes part of the cultural lore. Pretty sinister!

Whatever the chemical processes that underlie left-handedness—and there have been studies indicating a correlation with amounts of testosterone secreted during gestation—the cultural manifestation of raiding and warfare are clearly correlated with the human brain's cortical development rather than some ancestral remnant of vicious dragons. So much for the triune brain and "the dragons within."

To summarize: The triune brain concept continues to be popular because it supports an accepted but erroneous myth that man is disposed to violence and aggression due to the operations of evolutionarily old brain structures that lie buried deep in the core of his brain. However, it is not his core brain but *this very aptitude for myth* that distinguishes *homo sapiens sapiens* and leads to his aggressive behavior. Episodes become encoded in stories, in narratives. Narratives extend the potential effectiveness of an episode in time and amplify it in intensity: revenge, "an eye for an eye, a tooth for a tooth." The discriminative capacity of our brain cortex and its prodigious memory-processing capability carry the burden of ideological warfare.

The "Dragons of Eden" myth is faulty on anatomical, functional, and behavioral grounds. The acceptance of this myth does severe damage to the way we currently view all our social and political arrangements. In fact, we are neither helpless in the face of our basic instincts, nor do we need to "control them" by the use of our brain cortex. Rather, we must reorganize those political musings resulting from the operations of our cortex, which, when carried out in the extreme, wreak havoc upon the community of humans.

Currently, almost all practitioners of psychoanalysis as well as the lay public still espouse a version of the "dragon myth" by believing that the "superego" must keep the "id," the basic drives, the "dragons," in check. But that is contrary to what Freud said. As described in Chapter 12, Merton Gill and I document in our book *Freud's "Project" Reassessed* that for Freud, the superego, "the origin of all moral motives," is derived from what a caretaking, caring, person does to *satisfy* the needs of the baby, *not to prevent* satisfaction. We can cope with pains and pleasures, not by suppressing them, but by utilizing experiences gained from our caretakers. These acquired attitudes can become "dragons." The dragons are not instilled in us by our inherited biology or by our own experiences per se.

## The Cultural Context

Human biological evolution did not select for aggression. Hunting is, to a large extent, a cooperative venture. Gathering can be cooperative or performed in isolation. In neither activity is war-like aggression a required skill. Current non-industrial societies, like those in Borneo, have ways of facing off symbolically in a virtual reality—in a dance representing some tribal ideology. If someone is seriously hurt, both sides join in lamenting and mourning. Creating a virtual reality is, par excellence, a process dependent on the human brain cortex.

The Cold War was carried out in this same symbolic fashion: Five atom bombs on each side would have been enough to totally wipe out the "other side," but each side kept building more and more bombs in a dance carried out in a virtual world of deterrence. We were not really after each other's territory; we only wanted to project the grandeur of an idea, an ideology, communist or capitalist,

I had an interesting experience with regard to the crisis initiated by Soviet Premier Nikita Khrushchev when he started to build a missile site in Cuba that nearly turned a virtual reality into a real conflagration. I was in Moscow at the time, enjoying a great dinner served at the home of Leontiev, a high-ranking member of the Soviet scientific community. Conversation was lively and carried on almost simultaneously in four languages: Russian, English, German and French. Most of us could understand one or two but not all four languages. The topic of war came up: we drank to friendship. Without friends who could cross the barriers as we were doing, how could any war come to a halt? As far as I know, none of us was aware, as we drank our toasts of vodka, of the crisis taking place overseas—Leontiev might have known, but certainly did not let the rest of us know.

A few days later, as I traveled from Russia into Czechoslovakia, I encountered street demonstrations damning the Americans for our (failed) invasion of Cuba and for our resistance to having a friend (Russia) help a misunderstood (Cuban) populace. As the Cuban crisis was resolved and I came back to the States a few weeks later, I was to receive another surprise: Americans had been terribly afraid of the Russian incursion into our hemisphere so close to our border. On further inquiry, I learned that neither my Russian friends nor the Russian people in general could imagine that the great American nation might be afraid of a feeble marker—made of a few missile silos—set near their borders. After all, the Americans had missiles in the Pacific and in Western Europe that surrounded Russia at every corner.

From my experience with the Russian people, I began to realize something about the difference between the attitudes of the American and Russian people toward this virtual game of deterrence that was being played: I had once made an unintentionally offensive remark to friends in

Leningrad who had asked if I wanted to share a cup of coffee. I answered, “No, thanks—you Russians make wonderful tea, but your coffee is horrible.” Their reaction was a strong withdrawal, fortunately temporary, after I tried to make amends. I had insulted them and the culture they held dear. In the context of the Cuba affair, I realized that the Russians weren’t really afraid of us Americans and our bombs—they had much more serious problems to deal with right there in the Soviet Union. They felt *insulted* by our placing missile sites so close to their homeland. The truce was forged: we promised not to invade Cuba again; Adlai Stevenson arranged to have the most insulting of our missile sites, those in Turkey, removed.

These musings of mine are, of course, only part of the story. But much of the warfare waged by *homo sapiens sapiens*, the cortical primate, over the centuries *has* been carried out symbolically: Knights in armor tilting their lances and that sort of thing. Actual, real life bloodshed on a major scale came in with agriculture, an invention made by the cortical human whose memory processes engendered foresight. Agriculture allowed us to accumulate large stores of food, which could be stolen or traded for other goods; hence, agriculture marked the beginning both of realistic warfare and of business.

There is a human biological problem that is partially resolved through business: One male can fertilize many females. Thus, in any reproducing group, there are “surplus males,” which poses a problem for the group. These males have a choice of becoming integrated into the group, going elsewhere and starting a new group, or killing each other off. Historically, whenever territory was available, daughter groups were formed, and often there was interbreeding with the parent group. But when space is no longer available, frustration and territoriality can lead to emotional outbursts and aggression. With the advent of business, the surplus males can be sent out on the road, exchanging goods and services. Business keeps them busy and out of mischief.

But the accumulated stores of grains, livestock, materials and equipment can also attract human predators, raiders who “must” be repelled, lest all that stored “wealth” disappear. Before there were such large stores, accumulated at one site, the populace could flee, or leave a few token bits to appease the predators who weren’t really eager to fight when the possible rewards were so slim. Even from the socio-economic point of view, this is hardly the scene of packs of dragons looking for a fight.

It is time to re-emphasize the glory of our emotions and motivations, our feelings. Just as art, during the past century, has often focused on deformation, on the ugly, science too, as in the dragon myth, has focused on our flawed, deformed reptilian nature. But the time is now ripe—even long overdue—to re-emphasize the *constructive* shapes and patterns of human *forms of creativity*.

Even during my (now outgrown) radical behaviorist period, I wrote papers declaring the dignity of humankind. Aristotle noted that happiness is the pursuit of that which we are uniquely fitted to accomplish. We form and perform music, we build architectural edifices, we write poetic epics and novels, we construct engineering marvels, we create sumptuous menus for mouthwatering meals and formulate credible and incredible theories. Only the cortical primate accomplishes these *forms*—and only the cortical primate accomplishes the horrors of human warfare in the service of ideology and religion.

The "dragon"—if there is one—lies in our highly evolved and trainable cortex, not coiled like a serpent waiting to strike unless constantly controlled, buried in some ancestral remnant of the brain. So we need to remember: what is constructed cortically can also be deconstructed.

# Re-Formulations

# Chapter 18
## Evolution and Inherent Design

Wherein I explore the role of inherent design in the evolution of mind.

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*There have always been, and still are, reputable biologists who doubt that random hereditary changes can provide a sufficient basis for evolution . . . An organ like the eye is not simply a collection of elements—it is something which is gradually formed—.*

—C. H. Waddington, quoted in Arthur Koestler, *The Ghost in the Machine,* 1967

*The impotence of Darwinian theory in accounting for the molecular basis of life is evident not only from the analyses in this book, but also from the complete absence in the professional scientific literature of any detailed models by which complex biochemical systems could have been produced. The conclusion of intelligent design flows naturally from the data . . . design is evident when a number of separate, interacting components are ordered in such a way as to accomplish a function beyond the individual components. The greater the specificity of the interacting components required to produce the function, the greater is our confidence in the conclusion of design.*

—Michael J. Behe*, Darwin's Black Box,* 1996

*Darwin and evolution stand astride us, whatever the mutterings of creation scientists. But is the view right? Better, is the view adequate? I believe it is not. It is not that Darwin is wrong, but that he got hold of only part of the truth.*

—Stuart A. Kaufman, *The Origins of Order,* 1993

# Inherent Design

Gary Marcus has documented the observation that evolution has left us with a ”kluge,” a piecing together of working parts that are often far from ideally suited to accomplish the tasks we face. This is certainly correct. He uses the human backbone, the vertebral column, as an example. For those animals that walk on all fours, the backbone works well. For those of us who are bipedal, it often takes a bit of surgery to repair the damage that ordinary getting about produces. In our brains, the hippocampal system, the oldest piece of cortex, allows us to interleave neo-cortically organized cognitions into our emotional and motivational processes to determine our attitudes—with a variety of useful and deleterious consequences. But my favorite example of a kluge is the placement of sex between peep and poop. For most animals, and even for us, the kluge works because the dynamic evolutionary process of creating attractors builds on the ground plan with which we are endowed.

To achieve a working whole by putting together kluges, each kluge in itself needs to be formed. To achieve a working whole, *the formation of a kluge cannot solely be dependent on selection of possibilities created out of random variation.* And furthermore, as indicated in the quotation that introduces this chapter:

> “… [D]esign is evident when a number of separate, interacting components are ordered in such a way as to accomplish a function beyond the individual components. The greater the specificity of the interacting components [that is] required to produce the function, the greater is our confidence in the conclusion of design.“

To call evolutionary design “intelligent” (as proposed by current creationism) carries an unnecessary connotation of an agent. A more appropriate description is that the design is “inherent:” Acknowledging the inherent self-organizing processes that form attractors, stabilities far from equilibrium, enriches evolutionary theory; it does not diminish it. Furthermore, by acknowledging that *inherent design* plays an important role in the science of evolution, the wind is taken out of the creationists’ sails.

Dynamical system theory, the *formation* of stabilities far from equilibrium is not just a frill in our understanding of evolution. A complete theory of evolution needs to be based on the contextual *interrelatedness* of all parts of living beings and the interrelatedness of the living beings themselves. A *self-organizing diversity and refinement in design* is continually being created by these relationships. For humans, self-organization becomes extended throughout life by way of learning—which entails self-organizing processes in the *brain*. As described in the next chapter, this self-organization of the brain occurs by the same "genetic" process that formed the person initially. The result is a more or less inherently workable kluge which each of us experiences daily.

## Darwinian Evolution

The usual scientific explanation of how our minds have been achieved and how we form our civilization is by way of evolution. As noted in the introductory quotations, some theorists, by contrast, have proposed that we face the past and the future by way of "inherent design" that pervades the world we navigate. But these viewpoints are not really antagonistic: there is a complementarity between Darwin and Design. The complementarity involves classification, agriculture and horticulture, emphasis on processing and on complexity theory.

As Charles Darwin so beautifully described in his 1830s journals that recorded observations he made as he served as a naturalist on the HMS *Beagle* as it toured South America, the Galápagos Islands, Tahiti, Australia and New Zealand, a multitude of *unique* biological creatures populates the earth. Darwin noted the immense *diversity* of plants and animals and that each species was exquisitely *fitted* to its environmental niche.

For the most part, the *fit* is the result of environmental influences that shape the biology of the species, but, occasionally the species shapes its environment, as in the case of beavers building dams and sand crabs heaping sheltering mounds of sand. The ability to shape the environment reaches a zenith in *Sapiens sapiens*.

Darwin worked within a century-old tradition that had established a classification of biological organisms based on how closely organisms are related to one another. Carolus Linnaeus, during the 18th century had begun to classify this relatedness into orders, families, genera and species, depending on the closeness of the *relationship*. Closeness was determined not by surface similarity of form (called “phenotypic”)—such as that between whales and sharks—but by relations among deeper forms (called “genotypic”) that have to be diligently traced—such as that between whales and elephants. This distinction between surface form and deeper form is a theme relevant to how the human brain works, a theme we have encountered throughout *The Form Within*.

Before Darwin, the most expert 18th and early 19th century biologists, called “rational morphologists,” used the Linnaean classification to describe “laws of form.” The accomplishments of genetics now underpin Linnaeus’ observations and these laws of form by cataloguing the biochemical substrates—Desoxy Ribonucleic Acid (DNA) and Ribonucleic Acid (RNA)—of how the *relationship* among creatures actually becomes formed.

It was during the latter part of the 19th century that a focus on *process* began to surface. William James at Harvard University and Franz Brentano at the University of Vienna were concerned with the “stream” or “act” of thinking. Freud, a pupil of Brentano, developed a therapeutic technique based on process: the tracing of motives that determine the form of current experiences and behaviors. As we noted in Chapter 12, Freud recognized that motivation, the patterns by which we navigate our world, is formed by how we have processed our past, by our memory.

Darwin’s insight was based on the process utilized during millennia of human practice: the *diversification* and *selective breeding* of a variety of domestic *forms* through horticulture and agriculture. Agriculture and horticulture do not use radiation to change a character; the breeding process is much more deliberately designed. Darwin’s great contribution was to introduce *diversification* and selection to account for the *unique fittingness* of *all* biological creatures to their environmental habitats.

Selection was accomplished through survival by adapting to niches in an otherwise hostile and competitive physical and social environment.

The deep form (the genotype) of diversification came in part haphazardly, randomly, in part through sexual transactions. Sir John F. W. Herschel, Darwin’s teacher, countered that random variation could not account for the diversity of creatures; that some sort of design seemed to be at work. In the January 2009 *Scientific American* devoted to a comprehensive review of current Darwinian theory, Peter Ward, in an article on the future of human evolution, notes that "evolution has indeed shown at least one vector: toward increasing complexity." This increase in complexity is accomplished for the most part by regulatory genes operating within constraints. When the constraints are loosened, new stabilities far from equilibrium can become established. Thus we have at hand a viable theory of *inherent* complexity to supplement (not replace) "randomness" in accounting for diversity in evolutionary theory. Would Herschel approve?

## Forming Complexity

*In short, there appears indeed to be a considerable amount of "inherent design" not only in human achievements but in the natural order of the world we navigate*. It was left to 20th- century science to develop an experimentally based theory of design that complements current Darwinism. The theory, which we have repeatedly met in the experiments described in these chapters, is called "dynamical systems," "complexity" or "chaos theory." Ilya Prigogine, in a 1984 book *Order Out of Chaos,* showed how *temporary* stabilities develop in chemical processes far from equilibrium. The whirlpools that develop around rocks in a river are everyday examples of such temporary stabilities.

For the theory of evolution, dynamical systems theory provides a critical supplement to current evolutionary theory. Current theory awkwardly accounts for initiating variety in forms and their *refinement* by relying on random mutations. Such mutations more often than not eliminate an embryo rather than provide fruitful change. By contrast, self-organizing dynamic processes are inherently adaptive: *Once conditions are propitious, the self-organizing process tends to generate greater complexity.* Given tail feathers, a peacock has the potential, over generations, to decorate and display a fan of such feathers.

In an interesting article entitled "Complexity and Adaptability in Human Evolution," published in a volume entitled *Probing Human Origins* published in 2002 by the American Academy of Arts and Sciences, Richard Potts makes the case that in order for organisms, especially humans, to have persisted in variable, novel or shifting environments, *evolution of adaptability is essential*. Adjusting to environmental dynamics consists of *refining* adaptability by building a larger storehouse of alternative genetic variations; a greater phenotypic plasticity; and decoupling the organism from any single habitat—a freer mapping of behavior onto environment—in short a "complexity response."

Provided that specific complexity responses are not selected against, the discovery of stabilities far from equilibrium helps account for the progressive refinement we observe in the panoply of plants and animals, a refinement that cannot be accounted for by random mutation and sexual selection.

(For a detailed and exciting description of this theme (and his own research) see Stuart Kauffman, *At Home in the Universe: The Search for the Laws of Self-Organization and Complexity,* 1995.)

I hold that *adding self-organization to Darwinian theory is important because the form of the creatures we see around us need no longer be just those that are the product of survival of the toughest. The survivors can simply be decorative. Refinements of design such as the peacock's tail feathers, a human concerto, or the green and purple leaves in the trees of our gardens make for the beauties of nature and of human endeavors, important not only during sexual selection, but also for "us" to enjoy.*

The English language has an ambiguous meaning to the term "fit." Fit can mean "fittingness" as when a glove or a shoe "fits"—as Darwin described his observation during the voyage of the *Beagle*. Alternatively, "fit" can have the meaning of being tough rather than weak, as advertised by gyms and spas. Darwin shifted towards the meaning that fit means tough in his later writings and his supporters parlayed his ideas into "Social Darwinism," which declared that the tougher (that is, the wealthier) in our society are wealthier because their evolutionary heritage had made them "fitter." "Eugenics," a term coined by Darwin's cousin, Sir Francis Galton, the purposeful breeding of the fittest and the elimination of the unfit, became an early heritage of Darwinism.

In an essay (1985) Daniel Robinson, at that time head of the Department of Psychology at Georgetown University and I developed the theme, under the title "A Brainless and Mindless Evolutionary Psychology," that the (Darwinian) theory of evolution "displaced the individual organism, including human individuals, from the center of scientific concern and replaced it with the species en masse. Psychological individuality, like biological individuality, was simply one of the entries in the large table of natural variations from which the pressures of the environment would select winners and losers."

Skinner (1971)—whose more supportable contributions are described in other chapters—in tune with classical Darwinian theory, called for a society in which "the freedom and dignity of man were recognized as *anachronistic feelings of no utility in the process of survival*." Several of us were appalled and, in rebuttal, published a group of essays (1973) *Beyond the Punitive Society: Social and Political Aspects* (ed. Wheeler.) In my contribution, "Operant Behaviorism: Fact, Factory and Fantasy?" I declared that "Skinner accuses Koestler (some of whose work I have also quoted in other chapters) and rightly so, as being some seventy years out of date in misrepresenting behaviorism. But Skinner is equally out of date in misrepresenting the physical and biological sciences, especially in their information-processing aspects (and in misrepresenting the science of psychology itself). Perhaps that is why Skinner and Koestler found responsive chords in each other—we are privileged to watch and enjoy an encounter between such antediluvian titans."

## The Theme of Self-Organization

*Inherent design supplements and enriches the Darwinian approach to the process of evolution.* Our brain processes have made possible the age-long evolution of self-organizing structures. Freud described the memory-motive structures in the brain, showing that our cortex allows us to create greater *diversity*, making it possible for us to more capably handle *complexities* in navigating our world. What has been added since Freud is that this diversity stems from using the same genetic processes (algorithms in computer language) as those that form our heritage. But complexity describes not just the organization of the brain's substance but also the *form* that organizes brain processing and is organized by it. Cortical processes enable us to progressively self-organize; that is, to implement and experience ever more diverse and detailed memories and hence perceptions, attitudes and plans. The next chapter details how this is accomplished.

# Chapter 19
## Remembrance of Things Future

Wherein I continue to develop the theme that the brain encodes a compressed form of our experience, a pattern that serves as an attractor that guides us in navigating our world.

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> *. . . [T]he Muse of the Greek triad was named Mnemosyne, 'Memory, one can have memory of the future as well as of the past.'*
>
> —Robert Graves, *The White Goddess*, 1966

> *No preformed and complete structure has pre-existed anywhere, but the architectural plan for it was present in its very elements . . . The necessary information is present but unexpressed . . . the building of a structure is not a creation; it is a revelation.*
>
> —Jacques Monod, *Chance and Necessity,* 1970

## The Form of Memory

We call neural organizations that respond to *patterns* of excitation "memory," but biologists and psychologists refer to different processes when they use the term "memory." Biologists are interested in how patterns become stored and how the stored patterns become transformed over our lifetime. Psychologists are primarily interested in how we remember patterns that have been stored. When storage is holographic, the issue becomes how does a *dis-membered* store becomes *re-membered*?

## Remembering

The process of remembering comes in a variety of forms, each form dependent on the brain system involved:

1. One form of conscious remembering is composed of *episodes* of experienced events and eventualities. Episodic memory is formed by processes developed by the limbic basal ganglia such as the amygdala as well as by the hippocampus and the prefrontal cortex.
2. Remembering *skills and habits* depends on processing by the central part of the brain: the classical motor cortex and the corpus striatum (cau-date nucleus and putamen.) Skills are processed unconsciously: conscious intervention interferes with skilled performance. The saying "keep your eye on the ball" (not on your arm swinging a bat or tennis racquet) catches this aspect of skilled, habitual performance.
3. Remembering *names* (semantic memory) is processed by systems of posterior cortical convexity. We strive to do this consciously.
4. Remembering *images* such as visual images and music is processed by the primary sensory receiving systems, ordinarily a conscious process.

Remembering is dependent on having stored (biologically) what is being remembered. In addition the storage has to be organized if the stored contents are to be retrieved. Thus storage has another component: the stored items must be organized into labeled files—*codes*—that can be more or less easily accessed. Coding has to be part of the storage process. (The memory code basic to remembering is described later in this chapter.)

## Memory as Transformation

From the point of view of biologists, *memory* is embedded in matter, and matter, in turn, is embedded in memory. That is, the form of the memory-store becomes continually transformed: For instance, from genetic patterns contained in a small acorn, a great oak grows. And the oak reproduces that pattern in each acorn. Memory is a pattern that gives form to matter. In the quotation that opens this chapter, the great French biologist Jacques Monod has called memory an "architectural plan." Memory, when in use, is not just something stored in order to be retrieved. Rather, the initial form of memory is a potential to become revealed, the remembrance of an expression of something as yet unexpressed.

Thus memory is embedded at different scales of processing: from molecules and membranes, to cells and patches of fibers, to body systems including those in the brain—on to language, and to political, economic and social-cultural groupings.

Indeed, from this viewpoint, our language itself is a memory system that enfolds the wisdom of the ages. This view, which I share with many scientists like Monod, is directly opposed to that of the "eliminative materialists" encamped at the University of California at San Diego. These materialists hoped to eliminate what they condescendingly like to term "folk psychology" and would rather reduce our investigations to knowledge of brain function (sometimes, as constrained by the findings obtained in experimental psychology). The late Francis Crick, an advocate for the "eliminative" agenda, epitomized the extreme of this group's view when he stated, "If we knew what every neuron was doing, we could eliminate psychological formulations altogether."

By contrast, I hold that our language not only embodies our shared human experience but also provides us important entries to any meaningful investigation of brain function.

A prime example of my view is the word "mind." Its roots in Old English are *mynde* and *gemynde* meaning "memory." In turn *gemynde* was composed of *ge,* which meant "together" and *moneere* meaning to warn. Thus "mind" is based on memory and is used collectively to warn, or to keep an eye on things, as in "please mind the store while I'm away." Minding is attending, looking out and ahead, grounded on looking back and within.

There is both a retrospective and a *pro*spective aspect to memory. The retrospective aspect, re-membering, is familiar to us; its prospective function, as addressed by Monod, has rarely been emphasized in the brain or the behavioral sciences. The reason for this is that, until recently, we did not understand the specifics of how an acorn begets an oak tree or how a human sperm and an egg can blossom into the child you love. Memory *forms* our present which *determines* our future.

## Plus Ça Change

As the French saying goes, "The more things change the more they remain the same." Plants, insects, animals,— all things composed of biological matter actually depend for survival upon a fascinating ability to modify their memory without "changing" it. Our biological memory is often grounded in material components with a short "shelf life." In mammals, our red blood count itself varies little over time, yet each individual red blood cell disintegrates within a month. I was made aware of this short cell life in a dramatic episode: During World War II, we came to realize that blood serum divested of red cells was much more stable than whole blood and worked just as well to pull wounded soldiers out of shock. During my medical internship, I heard of a factory that was producing serum to send overseas. I asked what they were doing with the removed red cells: *nothing*. So I asked the factory to suspend the cells in a saline solution, bottle it, and give the bottles to me. I had established a small blood bank for my patients, using blood from their relatives, and these surplus red cells amplified the contributions to the bank.

All went well for several months until one day, using one of the bottles of red cells, I transfused a patient with ulcerative colitis who badly needed a large quantity of red cells. *Shortly she was passing reddish black urine.* This could be extremely dangerous if the hemoglobin of the disintegrated red cells should crystallize and block or damage her urinary system. I immediately neutralized the urine so that crystals would not form. I sat through the next hours with the patient, taking her blood pressure from time to time, chatting with her. She felt fine all day and had no adverse effects. With a sigh of relief, I called the factory to start controlling the date when the red cell samples were procured: No bottles were to be kept more than a week, lest the dis-integrating red cells leave us with "raw" hemoglobin. All went well thereafter.

The same functional stability in the face of cellular change is true of the brain. As we age, about 10% of our brain cells die off and fail to be replaced. However, the places emptied are quickly filled with new connections. Experiments performed during the early 1960s by some of my former students and their collaborators first indicated the magnitude of the opportunities to form such connections. The experiments were done in order to discern the location of the input to the cortex from the thalamus but unexpectedly yielded much more important results. A cyclotron was used to radiate the brains of rabbits. The cyclotron emits radiation that decelerates abruptly in soft tissue; thus circumscribed lesions can be made. The destruction is sufficiently local so that the usual reaction to grosser injury of neural tissue does not occur. Rather, space is made for active new growth of nerve fibers.

As detailed in my *Languages of the Brain* (1971), much to everyone's surprise, within two to three weeks . . . "large numbers of normal-appearing, well-directed fibers which were invisible either before or immediately after the exposure to the cyclotron" totally filled the space available.

These experiments were complemented by experiments on rats raised either in restricted environments or in cages filled with toys, tires suspended from the ceiling and so forth. "Comparison of the brains of animals reared under different conditions resulted in a measurable thickening of the cortex of rats given the richer experience."

The route to reaching this conclusion was not straightforward. The experimenters involved at the University of California at Berkeley (David Kretsch and Mark Rosenzweig) were interested in assessing the role of acetyl choline in learning. They found a 5% increase in acetylcho-line esterase, a compound involved in acetyl choline metabolism. Someone at the National Institutes of Health (NIH) which was funding the experiments, pointed out that there was at least a 5% error in the technique the experimenters were using. Also, the measurement of the cortical area excised as samples for chemical assay was deemed inaccurate. The NIH threatened to withdraw funding.

Several of my colleagues and I were appalled. Kretsch and Rosenzweig were acknowledged reputable scientists and professors. The funding was for a grant— not a contract. With a contract, the investigator is bound to carry out what he has applied to do. With a grant, the investigator is free to use the money for whatever research he/she chooses to pursue. If the granting agency disapproves, it does not need to renew the funding. But it cannot and should not interfere in midstream.

My colleagues and I got on the phone to NIH and the whole matter was dropped. But, properly, Kresch and Rosenzweig took the criticism to heart—as did their students. One of them solved the area-of-cortex issue immediately: he plunked the excised area of cortex into a beaker and accurately measured the displace volume of water—à la Archimedes. Marian Diamond, a superb neuro-anatomist, joined the project and found that the cortex of the "enriched" animals had thickened. Detailed histological analysis of the thickened cortex showed that "the number of nerve cells per unit volume actually decreased slightly. The large part of the thickening of the cortex was due to an increase in non-neural cells, the glia. Also, there was an increase in the number and distension of dendritic spines, small hair-like protrusions on dendrites, presumed sites of junctions between neurons." More on the role of glia shortly.

The impact of these findings can be gauged from the following incident. In the mid-1970s, the United Nations University hosted a conference in Paris on the subject of the brain/behavior relationship. The conference was very up-beat as we all had a great number of new findings to report. There was one exception: the reports made during one session on the progressive loss of brain cells during aging and other "insults" to the brain. For instance, a small blow to the head would result in the loss of thousands of brain cells.

I was sitting next to an elderly gentleman who progressively slouched further and further in his seat. In an attempt to cheer him up, I wrote a note to him regarding the research findings described above. The note worked. He sat up straight and listened more carefully to the ongoing presentation, and then left. We were not introduced; I gave my presentation somewhat later in the program.

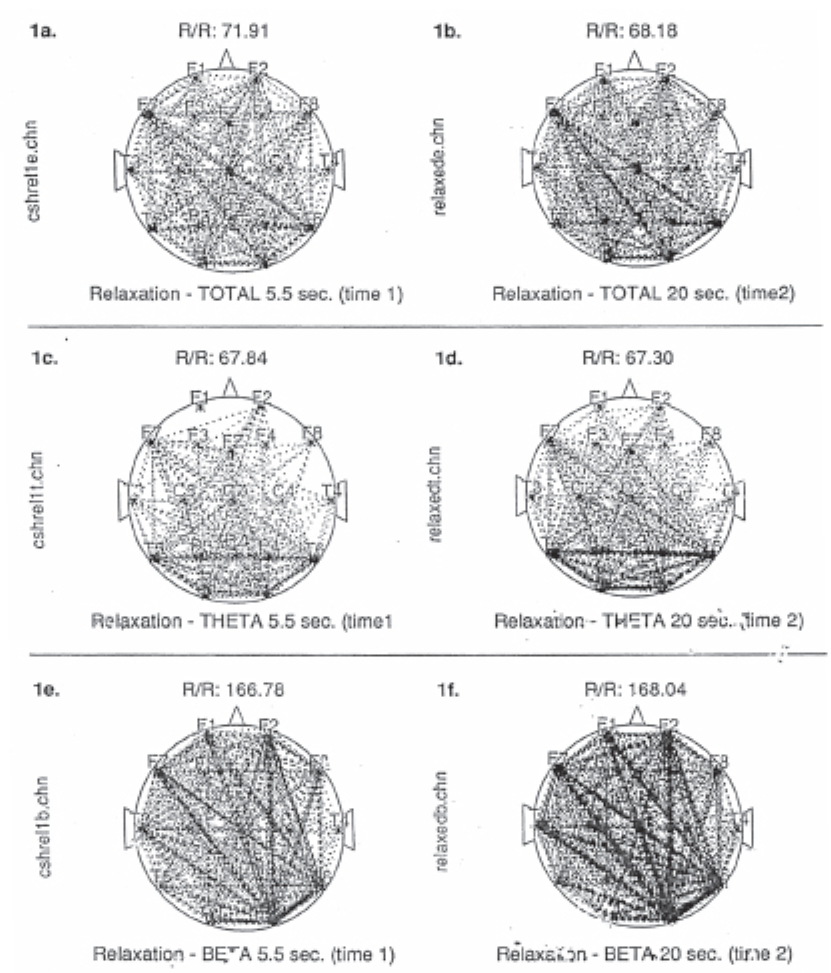
Imagine my surprise when the person asked to summarize the program was introduced: It was the elderly gentleman and his name was Lord Adrian, now 90 years of age. My further surprise came when Lord Adrian introduced his summary by stating how depressed he'd been by hearing about all the cell loss we experience, until "Dr. Pribram introduced me to new data that show that as cells disappear they make room for new connections to be made." He then gave a brilliant summary, mentioning from time to time that the results he was reviewing were making new connections in his brain!

The important point here is that biological memory is a form, a *pattern* that is composed of relations among parts, among shapes that are often individually, themselves, short-lived. Our skin, the linings of our lungs and intestines, and yes, even the brain, each cycle their component cells while maintaining their *form*—their structural integrity—their memory. In biology, psychology and computer science we therefore refer to *process*—the pattern of relations—as *structure*. Thus Miller, Galanter and I could write a book entitled *Plans and the Structure of Behavior* (as did Maurice Merleau-Ponty in his *The Structure of Behavior*), indicating that often brain and behavioral processes work in similar ways.

## The Being and Becoming of Electrical Brain Activity

In the early 1990s in my research laboratory in Virginia, we made a fascinating discovery, summarized briefly in Chapter 16, that should not have surprised us, but did. I had recently moved my laboratory from Stanford, California, and we were setting up new brain electrical recording equipment. I served as the first subject during tests of the equipment. I read, rested, and occasionally dropped off to sleep while we recorded my brain electrical activity. Min Xie, a superb researcher who had received his training in China and was now obtaining his PhD at Virginia Polytechnic Institute and University, recorded my brain waves. He selected, at two-millisecond intervals, the highest (squared) amplitude recorded from any point on my skull. The resulting video of my "brain scene" came as a complete surprise to me. The electrical activity of my brain changed so rapidly that it was hard for the computer to keep up with the rapid fluctuations. Once we were able to quantify what we had just recorded, we realized that my brain electrical activity was continually changing at the rate of around 100 times a second or more, no matter whether I was asleep or awake or what I was doing! How could we humans ever be able to construct memories of any duration, given this astonishing rate of fluctuation in brain activity?

The answer to this question came when we obtained another unexpected result. We now recorded from subjects who were performing a variety of tasks. Min Xie's wife, Bibo Xang, plotted the pattern of change in the location of the highest amplitude of brain activity recorded every 2 milliseconds. The patterns are shown in the accompanying figure. As might be expected, the brain patterns were unique to each individual and also differed from task to task. The surprise came when we repeated this experiment using recordings over longer periods—20 seconds instead of the original 5 seconds. *We found that the patterns were the same in the two recordings*. In fact, even after a lapse of six months, when we recorded from the same person performing the same tasks, we again saw nearly the same pattern. The patterns matched so closely from one recording to the next that I was actually able to identify the person whose record I was looking at.



These experimental results demonstrate a stability of pattern, of form, despite extremely rapid changes in our moment-to-moment brain electrical activity. I therefore searched for a measure that would demonstrate this stability. My intuition suggested that complexity theory (which also goes by the names “non-linear dynamics” and “chaos theory”) would provide the necessary measurements.

We tried several measures of complexity that had been developed in other laboratories but found that the EEG is produced by so many sources of variability that we could not tell whether the variability was random, produced by irrelevant changes (noise), or truly structured complexity.

Finally I got in touch with a friend, Paul Rapp, then of the Department of Neurology of Drexel University, who had been working on measuring the complexity of EEGs for a decade and was considered the “expert” in this line of research. He had published many papers by the time I got in touch with him. He was not very happy and was writing a critique of his own work! He had just realized that many of the measures he had used could not distinguish complexity from random fluctuations in the brain’s electrical activity.

But, as discussed in Chapter 16, he did have one technique that seemed to work: a data compression scheme that searches for a pattern that repeats itself within a string of symbols. To do this we take the EEG recording, one electrode at a time, and we follow that recording to where a change in the pattern of the electrical brain activity in that electrode takes place. We mark the pattern with a letter. We go along the record until another change in pattern occurs. If the next pattern is the same as the earlier one, we mark it with the same cipher. If the pattern is different we mark it with a different cipher. Next we go along the set of ciphers to see if there are any repetitions of sequences of ciphers. Next we go to a new level, generating a new shorter string until there are no repeats of identical strings. By proceeding to analyze the brain electrical activity in this fashion, one electrode at a time, we observed in each electrode more levels where repetitions occurred.

We analyzed the brain electrical activity obtained with 128 electrodes using this technique and found that the “algorithmic complexity,” as it is called, of the EEG increases significantly the older we get. Since the measure of algorithmic complexity was devised as a method of compressing data, this means that as we grow older our brains manage more and more to *compress our experienced memory*. No wonder it takes older people longer to remember, to decode the compressed experience, and to act on what they remember!

The results of this experiment, if they can be generalized, show that memory becomes compressed for proactive use, much as in a digital camera. You store the image until you are ready to use it (print it or store it in your computer.) As we will see, the process in the digital camera and in making images during tomography and fMRI follow the same principles as those we followed in processing our EEGs.

## A Useful Metaphor

Paul Smolensky, in a 1996 paper outlining the foundations of his harmonic theory of memory processing, wrote my favorite description of the *form*, the patterns that our cortical processing must take. Although it might be considered a masterpiece of indecipherable jargon, I like this quotation because it encapsulates both what the brain's self-organizing process, its memory, is *not* like and what it *has to be* like. Paul Smolensky puts it this way:

*The concept of memory retrieval is reformalized in terms of the continuous evolution of a dynamical system toward a point attractor whose position in the state space is the memory; you naturally get dynamics of the system so that its attractors are located where the memories are supposed to be; thus the principles of memory storage are even more unlike their symbolic counterparts than those of memory retrieval. (Smolensky, 1996)*

## Crystal Clear? No?

Here is an analogy, based on the fact that a musical tone can be described in terms of Gabor wavelets, that may help clarify Smolensky's meaning: "The concept of memory retrieval is somewhat like the concept of conducting an orchestra. At any moment, the performance is a dynamical evolution of musical phrases."

The evolution develops as a consequence of structured repetition. Leonard Bernstein exclaimed in one of his broadcasts: "Repetition, ah there's the rub!" In Chapter 16 and above I described the complexity of brain electrical recordings in terms of the structure of redundancy (repetition) that allowed us to *compress* a representation of brain electrical events into a hierarchically organized code. Formation of the hierarchy consists of a continuous evolution until the highest level of compression is achieved. This highest level constitutes an attractor toward which the process strives.

The complex sounds of music that make up a sonata can be similarly "chunked" and compressed into a hierarchy of phrases that are represented by the score. A score— the memory—is shared by the performers and guides the conductor who has the task of *de-compressing* the score in his own image. But the signs that are scrawled on the score and the gestures of the conductor are very unlike the music we actually hear. They are not just correlated with the music—they are *coordinate(d)* with what we experience.

Furthermore, the musical phrases are constrained by "bars" which indicate time limits on the expression of the tones. Tones are described in terms of their frequency while bars determine tempo. Thus, the musical form can be described as a windowed Fourier transformation, a Gabor function or related wavelet.

If we change this metaphor slightly, we can see that the "bars" of a symphony are very like the bar codes used today at supermarket checkout counters. The scan of the patterns of bars addresses the inventory (the musical tones) present in the store. The permutations of width and spacing are nearly infinite. The process is dynamic in that the store's inventory is updated with every sale. The bars in a score of music are constraints, the "windows" on the Fourier process that describes the tones that make up the Gabor-like windowed Fourier process.

Based on descriptions of the maps of receptive fields of cortical cells, I have proposed that the deep structure of our memory, as it is encoded in fine fibers in the brain, is much like a windowed Fourier transformation. The surface structure of memory, our retrieval and updating procedure, resembles what goes on at a checkout counter. It is only a step to conceive of a name as a bar-code trigger identifying a purchase.

The recording of a bar code form of memory has been recently accomplished. Joe Z. Tsien, now head of the Shanghai Institute of Brain Functional Genomics, translated the records of the activities of neural ensembles into a string of binary code in which a 1 represents an active state and 0 represents an inactive state for each coding unit. His recordings were made with an array of 260 electrodes that followed the activity of hippocampal cells in the laying down and retrieval of memories of startling events that mimicked a falling elevator or the shake of an earthquake. Tsien was able to predict within a 99% accuracy, which event had been experienced and where it had happened.

In my opinion, Smolensky's description, implemented by Tsien, encapsulates a great deal of wisdom. Smolensky alerts us to what memory in the brain is NOT. Whatever memory is, it cannot be described as having the same form as does our experience or behavior. Thus, *the forms of memory cannot be identical with those of our experience nor with the world we navigate; they are transformations that coordinate our experiences with that world. These transformations change the coordinates—for instance, firing rates of axons to a binary code and vice versa or neuro-nodal activity to [musical] scales and vice versa. Successive transformations form the oak from the acorn.*

# Order Out of Chaos and Autopoiesis

Another attempt to bring measurement to chaos theory was the concept of autopoiesis, or self-creation. Autopoiesis provides an important example of how we scientists often stumble onto refreshing ways of thinking about our existing observations. Francisco Varela, a Chilean biologist working in France, in his 1979 book *Principles of Biological Autonomy* wrote a highly technical and mathematical treatise on "autopoiesis," a term he coined. Autopoiesis appeared to me to be similar to the concept of "temporary stability far from equilibrium" for which Ilya Prigogine had received his Nobel Prize in Chemistry.

For instance, the pendulum of a grandfather clock under the influence of gravity swings to and fro until it comes to rest at the nadir, the bottom, of the arc described by the swing. But there is also another more temporary point of stability at the uppermost point, the zenith of the same arc. This feature of temporary stabilities is clearly demonstrated and used to good advantage in roller coasters and other "gravity defying" rides in amusement parks.

Temporary stabilities far from equilibrium are considered to be "attractors." The term "attractor" derives from the fact that we plot the paths by which the stabilities are attained. These path-plots serve to indicate where we will find the stabilities in the future. For a roller coaster, such plots are essential: we need to be sure that stabilities (far from equilibrium) over the course of the coaster remain stable lest some major tragedy occur. Thus these paths toward future stability serve as indicators as to where the stabilities are to be found. That is, they serve as attractors defining the future.

Prigogine and Isabelle Stenger's landmark 1984 book *Order Out of Chaos* describes the principles by which these findings are generated. The science of such temporary stabilities has since become known as "chaos theory." However, if we take into account these temporary stabilities (as for instance in our weather), "turbulence theory" might be a more appropriate term. Eddies that form around rocks in a river provide a good everyday example. The river flows by, always changing, but a visible pattern, the *form* of the eddies, remains constant.

One evening in 1962 when Francisco Varela and Ilya Prigogine were both dining at my home in Palo Alto, a heated argument took place: Prigogine insisted that Varela's autopoeisis was a totally different principle from Prigogine's forms of temporary stabilities. The argument was not settled that same evening, but shortly thereafter, our colleague and friend, the MIT mathematician Heinz von Förster, was able to clarify this issue to our common satisfaction: Varela had described form as *self-sustaining* despite changes of the system's components, while Prigogine—as detailed in his 1980 book *From Being to Becoming*—is instead describing the process of *initial formation*, the architectural plan by which such a system *self-organizes in order to become formed*.

But as we saw in the recordings of brain electrical activity and shall see throughout these chapters, both a self-sustaining and a self-creating system require some form of self organization.

## Are We Sleepwalkers?

Arthur Koestler's 1959 book *The Sleepwalkers* describes the partial and often befuddled insights of the scientists who initially changed the earth-centered view of the cosmos to a sun-centered view. Our understanding of such concepts develops gradually. Our current groping in the brain/behavioral sciences reminds me very much of this groping of the early cosmologists. For instance, we know that in AD 1500 Copernicus had already been informed by his contemporary Portuguese navigators about the discoveries, some two thousand years earlier, of Pythagorean astronomers and mathematicians. Aristarchus had shown, as early as 280 BC, that our cosmos was heliocentric, sun-centered. These early mathematicians had also figured out that the earth was round, and even, with surprising accuracy, what its circumference might be.

This same information—from the same Portuguese sources—was available to Columbus before he undertook his voyage of discovery. But Copernicus had been too unsure of his own rather sparse findings to publish them. His students prevailed. Copernicus's findings were published, and after his death his followers continued to promote his views. Kepler filled in the essential data that would have made Copernicus feel more secure in his views. Nevertheless, Kepler had still failed to attain the insight regarding the "forces"involved in securing the heliocentric view, which Galileo and Newton would provide, enabling us to complete what we now call the Copernican revolution.

## Remembering as Self-Organization

Ordinarily, *remembering* is divided into a short-term process, which George Miller, Eugene Galanter and I baptized a "working memory" in our 1960 book *Plans and the Structure of Behavior*, versus a process that persists for a longer period. Different brain processes serve these two different ways of remembering.

Psychologists have devoted considerable effort to investigating how short-term memory "consolidates" itself into a long-term store. During a series of conferences at Princeton in the 1960s that I organized and chaired, I addressed this issue. The proceedings were subsequently published in four volumes entitled *Learning, Remembering and Forgetting*. Among the notable scientists I had brought together at these conferences were my Stanford colleagues Gordon Bower and Richard Atkinson. Atkinson, with his student Al Shiffrin, had proposed a model of learning that still remains popular, in which they describe the progression of memory as moving from short- to long-term storage.

At these Princeton conferences, as well as later, I consistently disputed this model by pointing out that our short-term memory actually addresses our long-term store, since we pull out currently relevant items into a temporary "register" for current use. For instance, in a frequently used example, when we try to remember a phone number, we are addressing our long-term memory base of numbers, phones, phone books, and so on—a base from which we are able to *choose* the currently useful sequence of numbers. If that sequence becomes important to us, it must become incorporated into our long-term memory. *"Consolidation" is, therefore, not a solidification of an experience, as the term seems to imply. We use the short-term store to address and to transform our long-term memory—a working transformation that incorporates our current experience into our long-term memory to tag it as valuable for possible future use. Thus, remembering is a self-organizing process.*

Recently K. Nader and his colleagues (2004) have demonstrated such self-organization to occur by showing that the protein synthesis that takes place in the amygdala in the formation of a memory becomes "reconsolidated" with every new exposure to the provoking stimulus. Reconsolidation involves proteins that are configured differently from those taking part in initial consolidation.

Recall the experiments described earlier in this chapter, in which I showed that the structure of redundancy in the EEG *forms* the persistent pattern that we could recognize. According to the data just reviewed, this pattern becomes formed by "reconsolidation" at a rate of more than 100 times per second by the electrical patterns in the brain!

# Boning Up

In my 1971 book *Languages of the Brain*, I describe how our memory processes become formed by electrical excitation of a nerve cell. Such excitation leads to the activation of a messenger molecule—ribonucleic acid (RNA)— that, in turn, activates deoxyribonucleic acid (DNA), the molecule that carries our genetic memory. I based my description on the work of Holger Hyden, of the University of Gøtesberg in Sweden, who, as early as 1955 had shown that electrical stimulation of neurons leads to copious secretions of RNA which were transferred to the glial (Latin for "glue") cells surrounding a nerve cell. I conjectured that the RNA would then stimulate the glial cell to divide, and thus allow the nerve cell to grow and divide, making new fibers. The growth of the nerve fiber would thus be guided by the glia to make new connections—connections that would contribute a structural basis for forming our memory processes.

However, when I first read Hyden's reports on RNA and glial cells, I had some initial reservations. He claimed that he had dissected—by hand, under a microscope—glia from the nerve cells that they enveloped. I invited Hyden to a meeting sponsored by the University of California at San Francisco, and we soon became friends. It has been my habit, whenever possible, to visit a laboratory when the investigators report an important finding that puzzles me. So, shortly after the California meeting, I went to Sweden to see for myself how Hyden was performing his dissections. Hyden sat me down and handed me tissue from the vestibular nucleus of the brain stem, along with a microscope and a needle. By the end of the morning, my training in surgery had made me as adept as any of his staff at separating glia from neurons: I had a pile of nerve cells and a separate pile of glia cells ready for Hyden to measure the amounts of RNA in each.

Today and over the past few years, the focus of research on the secretion of RNA has been on the question of how its copious secretion is generated by nerve cells. The membranes of fine nerve cell fibers are composed of channels through which electrolytes—small molecules such as potassium—are exchanged. These electrolyte exchanges are regulated by the concentration of calcium. *Our brain cells live in a virtual sea of calcium ions*—that is, in a calcium-rich watery swamp just outside each cell's membrane, a swamp created by the phospholipid composition of the membrane. (The lipids compose the tough part of the membrane; the watery part is contributed by its phosphates.)

However, *within* an individual nerve cell and its fibers, the concentration of calcium ions is ordinarily extremely low: 20,000 times lower than the concentration outside the cell. When the electrical excitation of a nerve cell and its fibers reaches a certain threshold, the calcium channels open briefly. A spurt of calcium ions enters the nerve cell and initiates a chain reaction that activates a part of the DNA in the nucleus of the nerve cell to "liberate" messenger RNA into the cell's cytoplasm—and from there into the adjacent glia.

The most interesting part of the story (as told in *Scientific American,* February 2005) is that *it is not the amount of the electrical excitation that is important* in the transcription from the electrical to the chemical code.

Rather, it is *the form, the temporal and spatial pattern of the electrical signal, that becomes encoded in our brain cell's chemical transactions*.

As Douglas Fields, the author of the *Scientific American* article, put it: *"We observed that [electrical] signals of different temporal patterns propagated through [spatially] distinct pathways that were favorably tuned to those particular patterns and ultimately regulated different transcription factors and different genes."* [My emphasis.]

Where in our intact brains do such spatially distinct temporal patterns arise?

As a large nerve fiber approaches a synapse where it will connect with other cells, the large fiber branches into many fine fibers. I had recognized early in my research that learning ought to involve the strengthening of the synaptic bond of some of these branches, rather than all of them. But for years, I had no suggestion as to how such selective strengthening might occur. At many conferences over the years, my colleagues and I explored the possibility that feedback from postsynaptic sites could produce such selectivity—but for decades no evidence for such an effect was forthcoming.

However, recently evidence has accrued that *selectivity in the presynaptic fibers does result from feedback initiated by the postsynaptic membrane*. This evidence was obtained from recordings made in hippocampal tissue, and the selective feedback is potentiated chemically (by different endogenous cannibinoids).

The postsynaptic origin of this feedback accomplishes the selective presynaptic patterns of spatial and temporal frequencies described by Douglas Fields in his *Scientific American* article. *Such patterns, once initiated, perpetuate themselves and form the kernel for further development—the development of self-organized complexity.*

I love the fact that calcium ions play a significant part in the process of remembering: we really do "bone up" before an exam.

## Learning as Self-Organization

Operant conditioning is a vehicle for self-organization. In order to begin the conditioning procedure, we "shape" the animal's behavior by using a reward whenever the animal behaves in the way we want. *After that the animal (or human) controls his own opportunities to obtain* *rewards* in an ongoing self-organizing process. In Chapter 8, I explained the functions of the motor cortex as forming *"acts"*—that is, forms of activity that flexibly use component movements to *achieve targets*. As B. F. Skinner, professor of psychology at Harvard University, was fond of pointing out, the same is true of operant conditioning: For the experimental psychologist, "behavior" is not the description of a movement but ”the (paper) record the psychologist takes home at night to study." For the experimental psychologist, *”behavior" is an "act," an environmental consequence of movement, not a movement per se*. For Skinner it mattered not whether the behavioral record was made by the pecking of a pigeon, the press of a panel by a rat, or the depression of a lever by a monkey—or, for that matter, the repeated movement of a human.

I had great fun in using the operant technique during lectures given by Ilya Prigogine in the decades (1970s and 1980s) when we repeatedly interacted. I was always most interested in what Prigogine was saying and found myself making generally approving gestures. I noticed that Prigogine was moving toward where I was sitting in the front row of the lecture hall. So, on several occasions I deliberately continued nodding enthusiastically until Prigogine was eventually standing right in front of me and addressing his lecture to me, to the exclusion of the rest of the audience.

In my 1971 book *Languages of the Brain*, I note that there is continuity between how our bodies become organized as we are in the process of growing from an embryo and how our memories become organized as we are in the process of learning. In that book I spelled out the parallels that exist between our genetic development and how our behavior becomes conditioned. I suggested that our memories are "induced" in our brain much as our tissue development is "induced" during embryological development. Recently, my Georgetown students have updated this terminology by pointing out that induction is composed both of promoters and inhibitors.

In *Languages of the Brain* I outlined the similarity between biological induction (promotion and inhibition) as it occurs in embryological tissue and behavioral (psychological) reinforcement as it occurs during operant conditioning. The similarities are striking:

a. Inductors (like RNA) evoke and organize our embryonic *genetic* potential. *Reinforcers (in operant conditioning) evoke and organize our behavioral capacities.*
b. Inductors are specific in the patterns they evoke in a tissue, but they can evoke these patterns in all sorts of organisms and tissues. *Reinforcers are specific in the behaviors they condition but they can evoke them in all kinds of organisms—pigeons, rats monkeys or humans—and all kinds of tasks: running mazes, pressing levers, or capturing a lecturer's attention in a conference hall.*
c. Inductors determine the broad outlines of the induced pattern: that is, whether they are promoters or inhibitors; details are specified by the action of the substrate, the tissues upon which they are working. *Schedules of reinforcement determine the general pattern, increase or decrease, of the change in behavior; details such as pecking a panel, running in a running wheel, depressing a lever or turning toward someone in an audience, the details of the behavioral repertoire achieved are idiosyncratic to the organism.*
d. Inductors do not merely trigger our development; they are more than temporary stimuli. *Reinforcers do not just trigger changes in behavior during learning; they are a continuing influence on our behavior during subsequent performance.*
e. Inductors, in order to be effective, must be in intimate contact with the tissues, their substrate, upon which they are working. *Temporal and spatial proximity between a stimulus and the opportunity for response, such as a lever, is a demonstrated requirement for reinforcement to occur.*
f. Mere contact, though necessary, is insufficient to produce an inductive effect; the induced tissue must be ready, must be competent to react. *Mere proximity, though necessary, is insufficient to produce reinforcement: the organism must have previously been "shaped," that is, made ready, competent to learn.*
g. Induction usually proceeds via a two-way interaction between an agent and the substrate, the tissue, in which it operates—by way of a chemical conversation. Reinforcements, the consequences of behavior, become the "images of achievement," the targets of further actions.

Back in 1971, when I wrote *Languages of the Brain*, I also described a few chemical reactions that occurred in the brain during the reinforcement process. But at the time there were few experimental results to draw on that showed *how* the changes that occur could produce the *patterns* of learning and of memory. Since I wrote those passages, we have learned a good deal, as I'll describe in the next section.

## Creating Form in Biology, Brain and Behavior

In his superb 2004 book *The Birth of the Mind*, Gary Marcus addresses the very issue that had so concerned me in 1971: the connection I had sensed between our embryological development and the brain processes that are involved in learning and the formation of our memory. In what follows, I gratefully acknowledge my indebtedness to Marcus's detailed descriptions and his insights regarding the results of these recent experiments—insights which happily resonate with those that I had already begun to develop as early as the mid-1930s in an honors paper I wrote at the University of Chicago entitled "Meiosis and Syngamy." In that paper I described the importance of syngamy, a process in which a cell's mitochondria and other protoplasmic forms are guiding development through an interaction with the nucleus of the cell while it was dividing; that is, meiosis.

A great deal of current popular and even scientific thinking rests on the mistaken notion that there is some sort of one-to-one correspondence between a particular gene or portion of our DNA with a particular characteristic of our body, our brain, or our behavior. But as been effectively demonstrated by the Human Genome Project, we have too few genes to account for the incredible complexity of our bodies. Furthermore, the same DNA is involved in creating our nose as in creating our toes! The RNA generated by the DNA must somehow produce proteins that are specific to a nose or a toe. There must be some *local effect* produced by our cells, an effect that potentially composes a nose and a toe, and which also can determine their eventual difference. Neither the DNA itself (which is the same all over the body)—nor its RNA—determines characteristic membranes, organs and behaviors.

Gary Marcus invokes the particular *connections* of the cells as forming the substrate within which the RNA operates to express the DNA's potential. He notes that we can divide the *connections* in the brain into systems or modules: some are specialized for processing vision, others for processing hearing. However, Marcus indicates that specific patterns of genes do not characterize the formation of one or another module. Rather, the modules are determined by patterns of genetic molecules that operate as *gradients* that can overlap to produce the brain's modular structure. Thus, the discovery in my laboratory of receptive fields in the *visual* cortex that respond to specific bandwidths of *auditory* stimulation can be explained by such an overlap between auditory and visual genetic gradients.

Gary Marcus points out that the genes that produce genetic gradients do not operate singly, they work together in forming specific modules. Marcus uses chess as a metaphor to describe the power of genes to create diversity of patterns in our brains. He takes the example of a chess-board of 64 squares as the initial base upon which the game is to be played. There are thirty-two chess pieces (genes). They come in two sorts: black (promoters) and white (inhibitors)—sixteen of each. Let the game begin! A huge range of possible moves results in a mind-taxing set of patterns of moves (memories) on the chessboard and the resulting momentary patterns of arrangements of chess pieces. By dividing the chess pieces into only two categories, the game (the process) can generate an infinite variety of patterns from even a limited number of initial conditions.

Thus, the processes that operate in our brain that enable learning and that form our memories are identical to the genetic processes that initially form our bodies, brains and behaviors. Marcus sums up our insights elegantly:

> *Nature has been in the business of building biological structures for an awfully long time, enough to dope out many of the best tricks and . . . stingy enough to hold on to those tricks, once they were discovered. For the most part, what is good enough for the body is good enough for the brain . . . We can now understand better than ever just how deeply we share our heritage—physical and mental—with all creatures with whom we share our planet.*

## In Summary

I have emphasized several things we have learned about memory that are not commonly acknowledged in texts on how brain processes organize the form of memory.

*First*: Matter is embedded in memory. Memory is not matter itself, but memory is the *form* that organizes matter. Diamonds and coal are made of the same matter, but in its crystalline form, diamond is considerably different from a chunk of black soft coal.

*Second*: Our biological memory depends on "separating" a long-lasting *form* from its material components, the form of memory from its material substrate. In the philosophy of science this ability to separate *form* from substrate is more generally called "functionalism." It matters little whether the computer is an IBM, Dell or Apple. Properly constructed word-processing programs (plans) will run on any of them.

*Third*: Biological and especially brain memory is composed of complexly structured forms. A hierarchical structured memory is formed by repetitions from which identical repetitions of sequences are extracted and represented in a separate layer—a process that is repeated until no more identical sequences are formed. The hierarchy is thus a compressed representation (a code) of what is to be remembered.

*Fourth*: This compressed code serves as an attractor that guides navigating our world: memory is the basis for our ability to remember the future.

*Fifth*: Musical notation and superstore bar codes provide useful metaphors that allow us to formulate specific questions and answers about the design of our brain's processing procedures.

*Sixth*: The form of our memory is different from the form of our experience and of our behavior. Thus we ought not to be satisfied when we just correlate these forms. For full comprehension, we need to understand the "how" of the relation between them, how they become *co-ordinated*. Coordination involves *trans-formation*.

# Chapter 20
## Coordination and Transformation

Wherein I indicate that transformations among complementary formulations of brain/behavior/experience relationships often have greater explanatory power than do emergence and reduction.

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*You wonder that there are so few followers of the Pythagorean opinion, while I am astonished that there have been any up to this day who have embraced and followed it. Nor can I sufficiently admire the outstanding acumen of those who have taken hold of this [Pythagorian] opinion and accepted it as true: They have, through sheer force of intellect, done such violence to their own senses as to prefer what reason told them over that which sensible experience showed them to be the contrary.*

—Galileo Galilei, *Dialogue Concerning the Two Chief World Systems,* 1632

*"The other possibility leads in my opinion to a renunciation of the space-time continuum, and to a purely algebraic physics."*

—Albert Einstein quoted by Lee Smolin, *The New York Review of Books,* 2007

*One day William Rowan Hamilton . . . was crossing Phoenix Park in Dublin, when foreknowledge came to him of an order of mathematics which he called 'quaternians', so far in advance of contemporary mathematic development, that the gap has only recently been bridged by a long succession of mathematicians. All outstanding mathematicians have this power of making a prodigious mental leap into the dark and landing firmly on their* *feet. Clerk Maxwell is the best known case, and he gave away the secret of his 'unscientific' methods of thought by being such a poor accountant: he could arrive at the correct formula but had to rely on his colleagues to [try to] justify the result by pedestrian calculation.*

—Robert Graves, *The White Goddess,* 1966

# Coordinates

In the previous chapter I emphasized how changing coordinates— rather than just making correlations— is important to understanding current explorations in the behavioral and brain sciences. We must look to changes in "order," in the *co-ordin-ates* within which such descriptions are made.

In the chapter on codes and their transformations in *Languages of the Brain* (1971), I stated that:

> . . . whether something is remembered is in large part a function of the form and context in which it is experienced. In technical language this is the problem of transformations or transfer functions that make coding and recoding possible. When we address our computers in a natural language, such as English, that input is transformed via a series of processing 'languages' such as WORD, PASCAL and the like until the configuration of that language can address an octal (or hexadecimal) number code which, in turn, can communicate with the binary, on and off code of the computer hardware. In turn, when the computer has to communicate with my printer the reverse set of transformations has to occur.

When I was first confronted with a general purpose computer in the 1950s, it had to be started by entering a set of 20 commands, each command composed of setting a sequence of 12 switches in an up (on) or down (off) position. The demands on memory (20 times 12) were great: any single mistake would require the entire set to be repeated. Programmers were quick to get around this difficulty by "chunking," dividing the 12 switches into sets of three and labeling each set with a number:

0 indicates DDD; 1 indicates DDU; 2 indicates DUU; 3 indicates UDU; 4 indicates UDD; 5 indicates DUD; 6 indicates UUD; 7 indicates UUU. Thus the programmer had to remember only four numerals for each command (e.g. 1213.) This transformation is called an "octal" coding of a binary system. The coordinate "binary" was changed to the coordinate "octal." The procedure made possible a transformation from a pattern where complexity resides in the arrangement of simple elements to an

arrangement where complexity resides in the unique *meaning* of each component element. Today I would modify this statement only by noting that meaning does not reside in the component elements themselves; rather these elements are able *to convey meaning when placed in the appropriate context*.

Transformations due to changes in *coordinates* are not new, but their power *as such* has not been highlighted. As an earlier example, take our experience of the alternation of day and night. Early man observed the correlation of this alternation with the rising and setting of the sun. Our almanacs still indicate the time of sun*rise* and sun*set* for each day of the calendar, even though everyone is well aware that it is the Earth that is moving. Correlation is, however, the first step in our ability to come to an understanding of our observations.

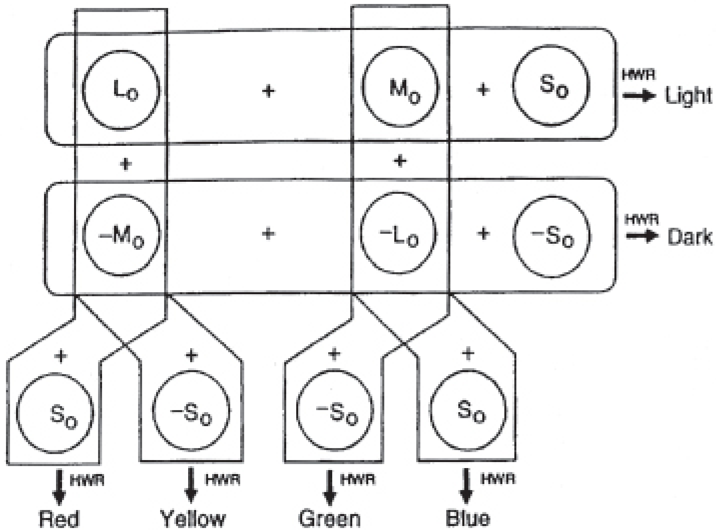
Many scientists and philosophers believe that the next step after correlation would be the establishing of an “efficient cause” that explains the relationship. In the above example, the “ efficient cause” of our experience of day and night is the alternation of “sun-rise and sun-set.” This is a step forward in relating the patterns of our experience to the patterns of the “cause” of those experiences. But to establish a meaningful understanding of the “cause” of the sun-rise and sun-set, and therefore of our experience of them, this is not enough. In fact, we now know that the sun does not rise or set: the Earth rotates around its axis, making it *appear* that the sun is rising and setting. This insight, a part of the Copernican revolution, demanded a total change in the coordinates that describe our experience: a change from coordinates centered on our earthbound experience to coordinates that centered on a rotating Earth—one that included a further set of coordinates that described the relation of the Earth to the sun—and later, yet another set of coordinates that included the relationship of the sun to its galaxy.

In a similar fashion, it is not enough for scientists to depend on studying simple correlations or even simple “cause-effect” relationships in our efforts to relate our brain processes to our experience or to our behavior. In order to understand *how* our brain processes relate to the organization of our behavior, as well as to the organization of our perceptions and feelings, we need to refresh our science, as indicated in the previous chapter, by establishing the coordinates of explanation at each scale of inquiry and changing the entire form of explanation from Aristotle's efficient to his formal causation.

Our perception of color can furnish us an excellent example of the transformations that occur as we process a bandwidth of radiation through our visual system. Processing in our retinal receptors is characterized by two or three bandwidths of sensitivity: low and middle frequency with a small contribution from a high frequency band. Within our retina these bandwidths are organized into three opponent processes: red-green, blue-yellow, black-white. As I noted earlier, such opponent sensitivities are arranged in the retina in a center-surround fashion. This is the first transformation.

Then, further along, deeper into the brain, at a later stage of processing, these opponent processes are subsequently reorganized into double opponent processes: that is, each color also "turns off" the part of its receptive field that had been turned on by its opponent. These changes are portrayed as the second transformation in coordinates within which each pair of colors is arranged.

Another example of a change in coordinates occurs when we are viewing a scene under infrared or ultraviolet illumination. We "see" as white what we experience as red under ordinary light; we "see" as yellow what we experience as blue under ordinary light. In general, the colors we perceive and the relationships among them are changed dramatically by changing the ambient light in which we are viewing the scene. The way we conceive of and perceive our "color universe" and the brain processes that enable those conceptions and perceptions changes radically when we take these observations into account.




*78. A complete diagram of the proposed stage 3. In the horizontal rows, cone-opponent units with the same center sign are added together (Lo + Mo +So) and (– Lo—Mo—So) to give achromatic units, since the luminance RFs of the cells add, but their color RFs cancel. In vertical columns, we add cone-opponent units of different center sign. Hence luminance signals cancel and color signals add. Note that S-opponent units serve a modulatory role, being added to or subtracted from each combination of Lo and Mo units. (From* Brain and Perception, *1991)*

# The Limitations of Eliminative Materialism

During periods of great change, holding to efficient causation provides temptations to exaggerate a particular view or a specific technology. These temptations seduce both the "old guard" and the "avant garde." I want next to call attention to some of these excesses.

Perhaps the most flagrant of the exaggerations is a popular movement called "eliminative materialism." In formulating a science that deals with the relationships among our brain, our behavior, and our experience, my efforts have been directly opposed to those of the "eliminatists" who claim that "If we could describe what every neuron is doing, we could supplant 'folk psychology' with neuro-science." In a sense, it is a return to behaviorism, but we are now asked to *identify* the efficient causal effects of the behavior of brain cells with those of the behavior of organisms, a mistake Skinner never made.

For the eliminatists, "Folk Psychology," expressed in everyday language, is to be eliminated because it is not sufficiently precise and is often misleading. By contrast, I have found much wisdom imbedded in our everyday use of words. I use the dictionary repeatedly when I am searching for an explanation of an unexpected laboratory or theoretical finding. For example, when I found, on the basis of my experiments concerning the amygdala and the hippo-campus, that episodes of our experience apparently *precede* the events that make up the episode, the dictionary told me that the word "event" comes from the Latin *ex-venire*, "out-come." So, *events are the outcomes of an experienced episode, the outcomes of, the consequences of an act!* Events don't just happen —they are "eventualities." Materialists face the problem of creating order among properties they observe and measure. Items whose properties are well defined often shed those properties when the items combine and new properties emerge. The standard example is water: hydrogen and oxygen are gases at earth temperatures, while water is liquid with peculiar properties such as wetness and flotation. Atoms are not "wet" even when they liquefy under pressure: they are apt to damage our skin. Wetness is a property that we come to explore from our experience with water. Once we have experienced wetness, we can try to find out what it is about water that makes it wet.

In studying the brain we need to take into account various levels of inquiry that reflect different scales of processing: the different functions of deep and surface structures; the modules and systems composing the brain; and the relations between brain systems and behavior, and between behavior and our conscious experience. When brain scientists try to formulate how, from the biological properties of nerve cells, such as a brain cell's electrical response, a person's or an animal's viewing of a hand or a face emerge, formulations quickly reach a limit. However, when complemented with a top-down approach, scientists can again make headway, as in the case of the discovery of cells electrically responsive to an organism's viewing of a hand or face. But to make such discoveries, there had to be a way to conceive of faces and hands—in this case, photos were available. Pictures and the words to describe them are the tools of communication in Folk Psychology.

My claim is that not only is it easier, but it is imperative, to start explicitly with our own experience, so richly expressed in the language of "Folk Psychology." But as cortical primates, we do not stop there: we continuously sharpen our experience by making ever more distinctions. In the case of the brain sciences, starting with observations of objects we call "faces" and "hands" allows us to determine not only their neural correlate but also how “higher-order” processes can influence, through *learning*, those of a lower order. Furthermore, the success of the Fourier-based harmonic analysis in describing processes in the primary visual cortex permits us to use a similar analysis to describe the temporal lobe’s processing of the fingers of the hand.

Reliance on efficient causation as it is applied in the description of emergent properties and the attempts at reduction of those properties to more elementary (material) entities is cumbersome and almost always ends in failure. A more comprehensive alternative is to relate the patterns, the forms of different orders, different scales, by relating them by way of transformation.

## The Limitation of Experimentation

Experimenters are tempted to conclude that the brain’s response to the stimulus they use—usually the one that is initially successful in eliciting a response—is a “*detector*” of that stimulus (e.g., a line.) The saying goes that when one has a hammer, everything looks like a nail. Today there is the constant danger that this error will be made in interpreting the results of brain imaging by tomography (PET scans) and functional magnetic resonance procedures (fMRI). When a brain area “lights up,” the temptation is to interpret that area as being a center for the single experience (such as “fear”) that is being tested.

Another example comes from the explorations begun in the feature and the frequency modes. Communication between the two schools of brain scientists has been limited, but engineers and mathematicians have been more creative in combining the contributions of each mode of investigation. One reason for a lack of communication within a particular branch of science is that laboratory research places constraints on experiments. On the positive side, this means that a clean result—an efficient causal trail—can be obtained when the experiment is well designed and carried out. But even here there is a caveat: the meaning of that result is frequently limited by the conditions of the experimental set-up. In other words, the result is often a foregone conclusion based on how the experiment was set up.

In order to overcome this limitation, experimental psychology went through a period of developing overarching grand theories that, however, often failed because they became too cumbersome when trying to encompass new data. As an example, in the 1950s, Clark Hull, professor of psychology at Yale University, tried to build an efficient causal input-output, behaviorist theory that would encompass the works of Pavlov, Freud and Thorndike. Hull developed equations in which the terms of the equations represented the results obtained from experiments and observations. He copied his approach from engineers, who are often faced with situations when an input and an output are known, but the experimenter has to determine what the intervening connecting factors might be. Hull's equations provided room for unknowns that would be found through further experimentation. This approach brought Hull a great following, and experiments on rats were performed in profusion at a great number of universities Each finding generated yet another equation until, at last, the whole structure fell of its own weight. About a month before Hull died, he said to me in discouragement, "Karl, this is no way to do science."

In reaction to this unwieldy process, several experimentalists, including Hull's pupil Jack Hilgard, suggested that experimentalists should develop mini-theories. But such mini-theories would fall into the very trap that the grand theories had attempted to escape. Each experimental result is, in itself, the test of a mini-theory: a *hypo-thesis*. In the clutter of hypothesis testing that soon engulfed experimental psychology and neuroscience, the *thesis*—the attempt to form a deeper understanding of *relationships to other data sources*—has tended to disappear.

There is a middle way between overarching theories and hypothesis testing: the key is to abandon deductive reasoning as the only "scientifically acceptable" route to understanding. Both of the extreme forms of doing science are based on deductive reasoning that, in turn, is based on efficient causation: grand theories such as Hull's made their postulates explicit; hypothesis testing often fails to do so.

In the mid-1960s the journal *Psychological Reviews* was installing a new editor, David Zeaman, professor of psychology at the University of Connecticut. While we were chatting, he said that his aim was to make the journal truly scientific: only papers based on deductive reasoning would be accepted. I was appalled. Most of psychology has not as yet gone through an inductive process that would lead to agreement on the names that identify processes, much less classifying these processes, classification that ought to precede deductive ordering. Exceptions have been psychophysics and, to some extent, developmental psychology.

Charles Sanders Peirce, the noted pragmatist, pointed out that both inductive and deductive reasoning bring little new to understanding in science. Induction organizes known observations while deduction places them into a formal relation with one another. To bring a fresh perspective, Peirce noted, one must use *abductive reasoning, that is, the use of simile, metaphor and analogy.*

The brain sciences have been enriched by the use of metaphor: We used to think of the brain as a telephone switchboard; this gave rise to the notion of the brain as an information processor. Then the metaphor changed to thinking of the brain as a computer; the computer taking the place of that angel, the switchboard operator. This metaphor gave rise to thinking of mental activity in terms of computer programs. The hologram is another such metaphor; this one accounts for maps of dendritic fields—and the psychological processes that cannot be organized by the neural circuitry of a telephone-computer-like system.

Metaphors are useful in bringing new perspectives to a problem. In science we proceed from metaphor to analogy, discerning which aspects of the metaphor are useful and which are to be discarded as inappropriate. We then proceed to making models that incorporate the new perspective into the data that gave rise to the problem. Dennis Gabor invented Fourier holograms mathematically; Emmet Leith made them palpable, using lasers. No one would take seriously that brain processes use actual laser beams—although one newspaper article proclaimed: "Stanford brain scientist finds laser beams in the head." Despite such fla-grant misunderstandings, progress was made during the 1970s and 1980s in sharpening Fourier-based mathematical models to map dendritic fields, what I have called deep processing in the brain.

Unfortunately, a sizable group of established scientists is always reluctant to accept the results of experiments when the data do not fit their own, usually unexamined, metaphorically based thinking. Today, findings that are framed within the metaphor of information processing based on *shape* are readily accepted: data concerning cortical columns, membrane channels and the molecules that traverse them. By contrast, data concerning *patterns* of transactions among oscillatory phenomena continue to have difficulty in being accepted, except where they have become standard fare, as in optics.

## Theses and Hypo-theses

A problem inherent in the limitations of current experimental science is in testing hypotheses. What is being tested is whether an efficient causal relationship exists between a proposition and its effect in the experimental situation. The idea is that deductive reasoning, hypothesis testing, can provide a hard-science explanation for the effects being investigated. This approach assumes that the observations and their relationships have been adequately examined and that there is no need for bringing in new perspectives. Neither of these assumptions currently holds for observations in the brain/behavior/experience sciences.

Hypothesis testing is useful in a circumscribed system where the tests *sharpen our focus on the assumptions* underlying the deductions that make up the system. The fallacy of much of current hypothesis testing in its search for efficient causal relationships—and especially of testing "what isn't," called "the null-hypothesis"—is that, in my experience, any reference to the *assumptions* in the deductive system is most often lacking. Reference to assumptions entails examining complexities, formal causal relationships.

Today, as I read current experimental reports, it is often hard to tell what results were obtained because they are buried in a welter of shorthand describing statistical significance. "Significance" suggests that the data were "signs" of something of importance—but that "something" is often hard to locate. The current overuse of the practice of formulating null-hypotheses—which, if disproven, prove that you were right all along—actually demonstrate that you didn't have to do the experiment since you already knew what you have now found out. The reason results of such experiments are so welcome is that they so often confirm what the experimenter and the scientific community think they already know.

Several papers have been delivered in recent years at the meetings of the American Psychological Association sharing my unease with what we teach, or fail to teach, our students. And in the January 2010 issue of the *American Psychologist* an article declared that "a quiet methodological revolution, a [statistical and mathematical] modeling revolution, has occurred over the past several decades, almost without discussion. In contrast, the 20th century ended with contentious argument over the utility of null hypothesis significance testing." The current revolution regarding learning and performance parallels that described as taking place a half century ago for understanding perception and memory storage, as described earlier in Chapter 2 of *The Form Within*.

## Pythagorean Pitfalls

Vision is not the only one of our sensory modes that has been afflicted by established scientific myopia! I was given a book, *The Emperor of Scent* authored by Chandler Burr, which chronicles the adventures of experimental scientist Luca Turin in trying to have his work published. Turin has a remarkable gift for distinguishing among, and identifying different odors. He is also a respected scientist who decided to find out how our sense of smell works. His research demonstrated that different odors could be identified by the different vibrations of chemicals that are absorbed by the receptors of our nose.

I had been interested in the possibility of resonance as a determinant of odors ever since the 1950s when, at Yale, Walter Miles told me that Michael Faraday had made just such a proposal in the early part of the 19th century. Faraday had been impressed with the capacity of the nasal chamber to maintain a stable environment of heat. "Heat" is radiation: it is a vibration whose wavelength is lower than that of infrared in the spectrum of "light." Faraday suggested that the olfactory mucosa absorbs molecules of olfactants (smells) that display different resonances.

Although the *vibratory* theory of olfaction has been mentioned, and to some extent tested occasionally since Faraday's day, the current establishment view is that the *shape* of the odorant molecule holds the key to its smell. Shape determines which molecules are absorbed by which nasal receptor. But shape and the patterns of vibration can be compatible: shape determines the location of the absorption; vibration is involved in the process by which the olfactants, once absorbed, stimulate the receptor membrane channels. The establishment, however, viewed Luca Turin's research as heresy. *The Emperor of Scent* details the results of his research and also his efforts to have the journal *Nature* publish the reports of his experiments.

Just recently (2006) the journal *Science* has reviewed this whole story on the occasion of the publication of Luca Turin's own book, *The Secret of Scent: Adventures in Perfume and the Science of Smell*. Turin describes his vibration theory in the context of chemical shape theories and notes the limitations of each. He concludes that there is no reason to exclude either theory, that they address different levels of processing—much as I had noted (before the publication of Turin's book, in the paragraph above). The reviewer for *Science* comes to the same conclusion.

I felt completely in tune with Chandler Burr's account covering the year and a half of carefully phrased rebuttals by Luca Turin to the wishy-washy replies of the journal's editor and to rejections by "peer review readers" for *Nature*—interestingly called "referees"—who seemed to have failed even to understand what his experiments were about. As I read, I was rooting for Turin and swearing at the referees. As do all laboratory scientists, I have a number of my own startling tales to tell.

*The issue is not whether the findings are "correct" but whether they are the result of a carefully carried out scientific procedure that can be duplicated by others.* In no case should hard data, the result of significant research, be kept from publication due to prejudices held by an established coterie. The advances of science depend on nourishing the enterprise of scientists, especially the young, whose paths to publication of the results of solid research should be nourished, not hindered.

As Chandler Burr puts it, in *The Emperor of Scent*:

> *It is therefore disorienting, almost surreal, to enter a story through one side and then gradually—I thought I must be imagining things—find that that side is so loathed by its opponents, so vilified by and toxic to them, and so axiomatically unworthy in their estimation of serious consideration that they actually refuse to share their own view with you.*
>
> *I began this book as a simple story of the creation of a scientific theory. But I continued it with growing awareness that it was, in fact, a larger, more complex story of scientific corruption—virulent and sadly human [in the] sense of jealousy and calcified minds and vested interests. That it was a scientific morality tale.*

But this is not the whole story. I have talked to my friends who have performed beautifully carried out experiments on the olfactory system and shown how patterns in the brain that are initiated by olfactants are sensitive to combinations with taste stimuli to form flavors and, in turn, how these “flavor” patterns are changed by more general perceptual and cognitive influences. What upset these investigators was the hyperbola of admiration of Turin’s work portrayed by Chandler Burr: stating that he should receive the Nobel Prize *as* ”The Emperor of Scent.”

Such excessive admiration comes when a particular discovery resonates with the personal experience of the admirer. Unfortunately, the admiration plays poorly with more established ways of doing science and therefore does more harm than good to the person admired. Achieving fame is a two-edged sword. Serious scientists, including Turin, with whom I’ve discussed this, prefer accountability and respectability.

## Fields and Things

The vibratory view of sensory perception has historically been harder to grasp because it relies on mathematical language that is unfamiliar to non-scientists and even to many scientists. Also, the vibratory theory is about relationships, oscillations, and patterns which can be mathematically described and even mapped. But they are not shapes and “things,” like points and lines, and thus not as tangible and familiar to us. In the latter part of the 19th and early part of the 20th centuries, great strides were made in our understanding of “things” in terms of the probability of their occurrence. This new approach overshadowed then-current theories such as those of Faraday and Clerk-Maxwell, based on relations. Interest in developing field theories gave way to thinking in terms of particles and lines (scalars and vectors).

The most famous example of describing the results of experiments in terms of particles rather than fields was when the German physicist Max Planck divided electricity and light into “electrons” and “photons.” Tremendous strides in understanding were achieved by such conceptualizations and then by naming them; nonetheless, the particle approach obscured the oscillatory properties of radiation— which had to be re-introduced in the 1920s by the French theoretical physicist Louis de Broglie in his doctoral dissertation, and by the Viennese atomic scientist

Schrödinger. As I've noted on several occasions, while we may be helped in our thinking by "thingifying and naming"—studied as "reification" in psychology—we are at the same time constrained by doing so. One of my most perceptive students noted, if "it" doesn't have a name, "it" doesn't exist. The converse of this is that if it has a name, it and *only* it exists. Quantum field theory has managed to overcome the constraints of reification, but many interpreters of the theory slip back into communicating in terms of things, which explains the often-voiced "weirdness" of the theory.

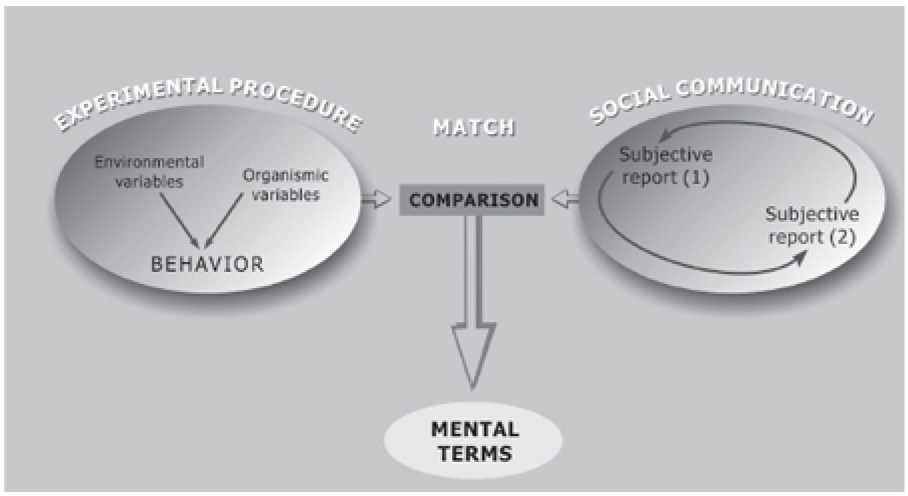
Just recently, I attended a lecture by Yakir Aharonov at a university in Jerusalem, a distinguished contributor to the current advances in quantum physics. In his talk, he used the term "electrons"—things—but when he made his formulations on the blackboard he drew wavelets when symbolizing them!

Once, while I was in Chicago visiting the Museum of Science and Industry, I came up with an interesting insight regarding statistics. I was attracted by a loud racket that proved to be caused by a display of falling steel balls ricocheting through a symmetrical plastic maze. The display had an explanatory card as well as a voice recording that described the importance of the "normal distribution"—the bell shaped statistical curve that had been formed by the balls as they landed. Nowhere in the description, visual or auditory, was there a mention of the symmetrical plastic maze through which the balls had tumbled. Without that symmetrical maze, the balls would have splattered on the floor in a flat plane. *Normal distributions reflect a symmetrical structure*.

Recently, several of my students at Georgetown University who were taking both physics and psychology courses were delighted when they learned about the relationship between such a normal distribution and symmetries.

## Complexity Theory and Formative Causation

*What this book is about is the search for "form"—that is formal rather than efficient causation.* Swedish physicist Niels Bohr gave a powerful example of the necessity to break out of the mold of efficient causality when dealing with newly discovered complexities. In a 1929 lecture before the Scandinavian Meeting of Natural Scientists, Bohr stated: “the domain of . . . quantum mechanics occupies . . . an intermediate position between the domain of applicability of the ideal of [an efficient] causal space-time description and the domain . . . characterized by teleological arguments.” Bohr correctly saw what was needed in the new enterprise and proposed the concept “complementarity” to deal with it. Transformations among complementary forms were focused by him on the type of measuring apparatus used (such as a single or double slit) in the experiments.




*79. An Example of Formative Causation*

J. A. Scott Kelso, in a book co-authored with David A. Engstrom *The Complementary Nature* (2006) has comprehensively reviewed “complementarity” as it forms and transforms the non-linear dynamics (chaos theory) of complexity. However Kelso uses the terms “complementarity” and “coordination” differently from the way I use them. For Kelso and Engstrom complementarity is, among other things, something like a symmetry set, a mirror image. Co-ordination is the way several sets of variables become integrated—but not specifically by relating them by way of separate coordinates, as I am proposing here.

We have available today a formal procedure by which we can study the domain intermediate between efficient causality and teleological arguments. As noted in Kelso’s work, we can now describe, with the techniques of non-linear dynamical systems, the relationship between initiating conditions, complex self-organizing processes, and the outcomes of those processes. The procedure entails repeating an observation a sufficient number of times until a reliable pattern emerges—emerges out of the "noise," that is, out of non-repeatable observations. The resulting pattern is called "a basin of *attractors*." The attractors, as their name applies, indicate the destination toward which the process is headed, Aristotle's "final causation." But more than final causes can be plotted: slices, sections, can be made across the basin of attractors to ascertain the form of the paths taken *during* the process. This formal process I have referred to as "formative" because it is proactive. Formative causation is called by a variety of names: complexity theory, non-linear dynamics, dynamical systems theory, chaos theory. In Bohr's domain of quantum theory, Yakir Aharonov recently proposed a technique of "weak measurement" that develops a set of "history" vectors and another set, "destiny" vectors, that describe the complexity of quantum transactions.

The simplest example of the construction of a basin of attractors is tracing the path of a pendulum. If the pendulum is not energized, it comes to rest at a point. Its path is simple to chart, and the rest point is a "point attractor." If the pendulum or a swing at a country fair is swung with sufficient or repetitive force, a second hesitation, a temporary stability in the path, occurs at the zenith of the swing, far from its nadir at equilibrium. Thus two point attractors are described. When the to and fro of the device becomes more permanently energized into an oscillation, a "periodic attractor" is described.

Much more complex paths are described if the shaft of the pendulum has a joint in it or a device (or a system such as the solar system) has three rather than two oscillating elements. But beginnings have been made in describing the paths taken to such multiple or "chaotic attractors." These techniques are truly in the spirit of formative causation and have been taken up when relevant throughout the chapters of this book.

My colleague at Georgetown University and an Oxford don, Professor Rom Harré, recently has made an insightful proposal that articulates the manner in which formative causation applies to the concepts of emergence and reduction. Harré suggests that structures can be considered to be *complementary forms* that need not be viewed as entities composed of components. In this view, scientists, philosophers, and I are spared trying to overcome the limitations of viewing relationships as consisting of an emergent that needs to be reduced to its components. *Rather, the relationship between complementary forms becomes a search for* *transformations,* as in relating one level of computer programming to another. Mathematically, the search consists of specifying the transfer functions that relate one form to another.

Different tools of observation provide complementary forms. In 1929, physicist Niels Bohr wrote that "in the domain of atomic theory . . . the usual idealization of a sharp distinction between phenomena and their observation breaks down." Bohr went on to describe differences in observations made using different instruments as yielding "complementary" results: Is the *form* of subatomic phenomena to be conceived in terms of waves?—or particles? or both? I have appended a paper (See Appenndix A: "Minding Quanta and the Cosmos") describing how our biological apparatus constructs our experiences (phenomena) and complementary theories about those experiences.

Formal, formative causation and non-linear dynamics are the tools Bohr sought. Those tools have become available to us in exploring the complex phenomena that are being discovered in exploring the brain processes that guide us in navigating our universe.

Viewing relationships among complementary forms in terms of transformations provides a fresh perspective on emergence and reduction. The ordinary approach to emergence focuses on the emergence of properties, usually material properties, whereas approaching emergence from the standpoint of transformations entails *the specification of transfer functions, of translational forms*. Transformations of acorns to oak trees, embryos to children and then to adults are prime examples of the development of complexity, the development of complementary forms through transformations.

Transformation also gives a different flavor to reduction. By specifying the transfer functions that relate one form to another, a common vocabulary relates one form to another. The periodic table of elements, the most successful attempt at reduction, is a prime example of the reduction among forms: chemical forms to atomic forms by way of the transfer function "atomic number."

The coordinates of the patterns of our conscious experience are formed by transformations that can be specified by their transfer functions from (complementary forms of) the patterns of our brain processes. Equally important, the patterns of our brain processes are formed by transformations that can be specified by their transfer functions from (complementary forms of) the patterns of our conscious experience. The remaining chapters of this book continue to specify these coordinate transformations.

In any of these ways of dealing with the mind/brain relationship we are using the structure of language to talk about what it is that we are talking about. In one case, brain is the subject and mind (psychological processes) is the object. In the second way of approaching the relationship, our experience is the subject exploring brain as the object. As in the case of seeing red, does the language reflect our mode of analysis or is the mode of analysis a reflection of language? Or both?

Taking the route of “both” lands us in a different sort of dilemma. Do brain and psychological processes coexist without interacting, or do they interact? (Coexistence is called “parallelism”—the position advocated by Ernst Mach, a position rebelled against by the philosophers of the Vienna circle and by Karl Popper). Karl Popper and John Eccles, though they differed considerably in their approach to the problem, espoused the interaction view and wrote a book together. Popper traced the interaction between psychological processes and the brain through culture; Eccles had mind operating directly on brain, which poses the problem of how this can be accomplished.

Popper’s way affords a simple answer: We do something or communicate something. This influences others in our culture who then implement the idea, and we experience the implementation through our senses, which in turn influence our brain. I have added that we can influence our brains through our bodies and through sensing our behavior, not only through culture.

I also hold that much of conscious experience does not *immediately* become embodied. I look at the flowering spring landscape—perhaps this produces an endocrine surge (of adrenal cortical hormone)—but perhaps not. Much of what I experience consciously, what I sense or think about, is just that—an epiphenomenon, as philosophers call it. Only when the experience has consequences—and is thus embodied (embedded) in memory—does it fulfill the requirements of downward causation.

But this brings me to Lévi-Strauss’ injunction: when we are dealing with complexity, the efficient causal approach fails—we need to look at the formal structure of the problem. It really is not much help if we phrase the mind/ brain issue as ”an egg is a chicken’s way of reproducing” or “ a chicken is an egg's way of reproducing." Neither tells us much about the composition of chickens or eggs.

# Free Will

I want now to illustrate the power of taking formal causation seriously by initiating a discussion of one of the most debated issues within the brain and behavioral sciences: the question of whether or not we are capable of acting deliberately. The debate centers on whether we can voluntarily "cause" our actions (in the sense of efficient causation).

With respect to free will, dynamical systems descriptions of attractor basins—descriptions of sections through the variety of "paths" taken by brain processes involved in forming the basins—are much more appropriate to charting the degrees of freedom of action within which we operate than any attempt to use, in the sense of "efficient causation," the time course of a single brain event as "causing" or "not causing" a willed muscle contraction or movement.

In order to behave deliberately, by definition, we must be aware—that is conscious—of what we are about to do. However, brain scientists have recorded changes in the human brain cortex that are correlated with action, but occur a half second or more before a person becomes consciously aware that he or she is about to act. (I have seen such anticipatory electrical events occurring even earlier in the brain stem.) These "readiness potentials," as they are called, have been interpreted to mean that volition at best can stop a neural "program" that is already set to go. The conclusion reached by many scientists and philosophers is that we, as conscious subjective beings, are pretty much at the mercy of whatever has set our behavior in motion and that free will is an illusion: the initiating event, whether a tennis ball approaching my tennis racquet or someone asking me to raise my arm, initiates a process beyond my control, a process predetermined. In analogy to David Hume's example, it is as if the cock's crowing were causing the sun's rising.

We already know from experiments performed in the 19th century that what we are aware of is an entire situation within which a behavior occurs, not the particular muscle groups involved in the activity. Hermann von Helmholtz in Berlin had analyzed the difference between automatic and voluntary behavior and had shown that voluntary behavior involves a simultaneous and parallel activation of two brain systems. Helmholtz demonstrated this by paralyzing the eye muscles of a test subject and asking the person to move his eyes. As a result, the scene flashed across the person's visual field as if a screen—a "frame" upon which the visual world had been projected—had been moved. Recently, experiments have shown that this frame is "constructed" by brain cells near those that control eye movements in the brain stem. Thus, Helmholtz demonstrated that seeing a scene by voluntarily moving our eyes depends on two outputs from the brain: one moves the muscles of the eye, the other compensates for the movement.

In order to voluntarily move an arm, we must already be aware of the "frames" or contexts within which to move it. There is a visual frame, a body frame, and the frame of the muscles of the arm itself. The experiments that describe the readiness potential address only the movement, the sequence of muscular contractions—not the visual or total body frame within which the movement takes place. As in so many of the more encompassing brain/behavior relations, several brain (and body) systems are enlisted in willing an action to occur. And it takes around a half- second (called the "reaction time") to mobilize these several systems and our awareness that they have been activated.

But the willed action does not consist of "telling" each muscle what to do. Rather, the motto "Keep your eye on the ball" is more appropriate. In tennis or baseball, we are not consciously aware of the arm that holds the racquet or the bat. We are aware instead of the context of the game, focusing on the ball, but also on the position of other players, the boundaries of the playing field, and so on. The context provides constraints within which we voluntarily play the game.

My willed behavior is subject to a variety of constraints such as gravity, the clothes I wear, the values that I hold dear, and the social situation within which my behavior is intended. Actions that are available to us within the context of various constraints are described scientifically as operating within certain degrees of freedom. Subject to these constraints or limitations, however, I can act, seek to experience and express myself freely. We "cause" our actions, but not in the immediate "efficient causal" sense. We often act with an eye to the future, a final cause. And, within the larger context provided by the degrees of freedom that characterize the situation, our wills operate by way of formal causation.

Efficient causality is practical and effective in explaining how we solve problems in limited and simple situations. It fails to resolve more complex issues such as "free will" because the richness of relationships we study in brain/behavior/experience science demand enlisting the more comprehensive formal causation in order to foster understanding.

## What *Do* Brain Processes Look Like?

While lecturing to students at Harvard one summer, with the psychology faculty sitting in the back row of the classroom, I was introduced to the folly of what happens when we expect brain processes to look like our experience. My lectures are always informal in order to encourage active audience participation. In this case, the faculty needed little encouragement and pitched in whenever they felt it to be appropriate. George Miller and I had already forged the friendship that shortly was to produce our book *Plans and the Structure of Behavior*. Because Miller is very tall, he occasionally leapt up in class to clarify a point at issue, using the top half of the blackboard that I hadn't been able to reach. Students, faculty and I have all looked back at that summer as both illuminating and fun.

B. F. "Fred" Skinner and I tackled many questions we held in common, such as what might be the brain structures that organize the process of reinforcement during conditioning. One day during that summer's Harvard class, he surprised me by asking, "Karl, what is your position on isomorphism?" (As noted earlier, isomorphism—*iso*, "same"; *morph*, "shape"—refers to the proposal that brain processes are shaped geometrically the same as the shapes we perceive.) I replied that there must be something going on in the brain that makes it possible for us to get around, something that allows us to navigate our surroundings. Skinner then said, "Imagine what is going on in your brain when you are watching green grass growing in your lawn. Pause. Now imagine mowing that lawn." Of course I immediately saw a lawn mower sweeping across my brain cortex that had sprouted green grass.

No. The brain doesn't work that way. Still, my reply to Skinner's question had to be, in some respect, correct: processes in our brain must, in some significant fashion, reflect our surroundings.

A half-century after that Harvard class in which Skinner posed his question, I can now answer it in detail: there are *trans-formations* of the world-out-there into the processes of perception and memory going on in our brain, and there are also *trans-formations* that change our brain processes into our ability to undertake effective action. The relationship is algebraic, Pythagorean, not geometric.

## Coordination as the Basis for Transformation

Most often, brain scientists and psychologists are satisfied when they can establish correlations between mental and brain processes. This is an important first step but does not describe the processes by which those correlations are achieved. My interest in the mind/brain relationship goes beyond correlation: ***How Do*** *brain and mental processes become coordinated*?

My answer, since the 1960s, has been that our brain processes become coordinate with our behavior and our experience by *trans-formations*, that is, by *changes in form*. *Changes in form are accomplished by modifying coordinate structures, such as those composing our memory, that form the relationship of our experience to our brain.* Examples of such changes in coordinates are a change from two to three dimensions in a visual scene, or a change from an Earth-centered to a sun-centered cosmic system. *Coordination describes relationships among the coordinates themselves.* (Hertz referred to changes in such relations among coordinates as “holonomic transformations,” a term that I have adopted.) The coordinates that form brain systems are certainly different from those that form behavior and experience, as those who are trying to create prostheses are finding out.

*Changes in form, transformations, describe living a life.* The acorn changes its form as it grows into an oak tree. The same constituents, carbon, nitrogen, oxygen, water and more complex molecules, take on, not only different arrangements, different *shapes*, but also different *patterns* of relationships with their environment. Initially, prompted by their ability to include the radiation from the sun and nutrients from the soil, these forms produce changes in form, transformations, in their environment. Trees and other plants transform the climate. In Ankara, Turkey, the university planted acres and acres of trees. After a few decades, heavy rains and snowfalls were recorded for the first time in over a century. Beavers make dams and change streams into ponds. Humans build dams and roads—and houses that hold paintings and libraries that hold books and concert halls in which glorious music is performed. The changes in form, the transformations that characterize human culture, are even more *differentiated*—make more distinctions—than those of plants and non-human animals.

In order to accomplish these transformational processes, the processes must, at the same time, be stable and dynamically adaptive—continuously changing. The *form* of the process provides stability while the substance can change with regard to biological memory. The unchanging form can also be enshrined in a library of books, in the architecture of a cathedral, or in the stories we tell our children. In short, much of the stability of remembrances-of-things-future is embedded both in our brain and in human *culture*.

## Transformational Realism

Are our experiences *constructed* by way of transformations? Or are they ”real”? Philosophers have argued the pros and cons of this question. What I have reviewed in this and previous chapters indicates that forms are constructed by transformations that coordinate a distributed brain process that “looks like” nothing that we experience. Are our experiences therefore not “real”? Of course they are. When I bump my shin on a bed rail as I‘m about to climb in, I experience the resulting pain as real—my endorphins are low and it hurts like hell. But our reality is constructed. When we are babies, we encounter the world we navigate with the variety of our senses. Each sense provides a wholly different experience. Somewhere, early on, we fuse those disparate experiences, different perceptions into a single coherent reality. The process continues as we navigate our social world and is called “consensual (putting our sensations together) validation.” I like to tease my fellow philosophers by noting that those who don’t make that consensual transition become solipsists: philosophers who question reality.

Despite the explanatory power for ordinary communication that follows from an emphasis on form and transformation, there are also stable forms of memory embedded in the brain that do not fit the transformational explanation. These forms of memory can lead to extraordinary feats of remembering. We ordinarily remember the alphabet, simple multiplications and names (most of the time); however, there are phenomenal feats of remembering that defy us to formulate questions as to how they are constituted.

I have heard a six-year-old girl listen to a piano sonata once and then play it without a score, beautifully, with feeling. Luria has documented the performance of a mnemonist who remembered everything to the point where he was unable to make ordinary life choices.

This extraordinary sort of memory is called “eidetic.” It is most common in children and disappears with the surge of sex hormones at puberty. One of my colleagues studied a young lady whose eidetic memory allowed her to see a figure that ordinarily depended on binocular vision (using both eyes at once) when several days elapsed between exposure to one eye and the other. She had an excellent “ordinary” memory and was very clear as to which type of memory she was using. As so often happens, my colleague and his subject fell in love, married and had children. With each pregnancy (with its endocrine upheavals) the eidetic memory faded more. My colleague had to turn to other aspects of psychophysics.

I have not been able to formulate even a reasonable question that would address how the brain makes eidetic memory possible. This contrasts with so many questions that have been posed and answered over the past half century. The journey is not completed.

# In Summary

In this chapter I have indicated how the use of formative causation as applied to coordination and to transformation can resolve some (but not all) puzzling results of experiments obtained in the brain/behavioral/experiential sciences. A prime example has been the difficulty in obtaining acceptance by established journals and granting agencies of work that has shown how vibratory phenomena can lead to perception: the dominance of theories of shape (chemistry, lines as features) has blinded reviewers to the possibility that both shape and pattern can be related to one another via transformation (transfer functions). Another prime example was how a resort to correlations gave a very limited view to our experience of free will. These examples were supplemented by a journey through the limits of some current practices in the behavioral and brain sciences. The chapter ends with some more history and insights into the importance of transformation in the establishment of memory—in anticipation of the topics of language and consciousness taken up in the next chapters.

# Chapter 21
## Minding the Brain

Wherein I propose that Aristotle's formal, formative causation is more appropriate to understanding complex brain/behavior/experience relationships such as "free will" than the more routinely applied efficient causality.

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*The pendulum has been swinging; its ticking will be heard through the entire course of history, as the blob alternates between the extreme positions of 'all is body' to 'all is mind', as the emphasis shifts from 'substance' to 'form'—from atoms to patterns,—and back again.*

—Arthur Koestler, *The Sleepwalkers,* 1959

*The Pythagoreans' chief accent was on form, proportion, and pattern; on the eidos and schema, on the relation, not on the relata. . . . [Their] vision of the world was so enduring, that it still permeates our thinking, even our vocabulary. The very term philosophy is Pythagorean in origin. The essence and power of that vision lies in its all-embracing unifying character; it unites religion and science, mathematics and music, medicine and cosmology, body, mind and spirit in an inspired and luminous synthesis. It was the first step toward the mathematization of human experience—and therefore the beginning of science.*

—Arthur Koestler, *The Sleepwalkers,* 1959

*. . . {N}umber now appears in physics as the only entity with sufficient permanence to be taken seriously by the physicist. It is but a step from this to the assertion of the Pythagoreans that*

*numbers are the very essence of things.—An essential Pythagoreanism is called for . . . (provided, of course, any mystical or magical implication of the term is duly discarded.)*

—Bernard d'Espagnat, *In Search of Reality*

*Have I not erred in applying to historical thought, which is the study of living creatures, a scientific method of thought which has been devised for thinking about inanimate Nature? And have I not also erred further in treating the outcomes of encounters between persons as cases of the operation of cause and effect? The effect of a cause is inevitable, invariable and predictable. But the initiative that is taken by one or other of the live parties to an encounter is not a cause; it is a challenge.*

—Arnold Toynbee, *A Study of History,* 1972

# Coordinating Mind Talk and Brain Talk

For millennia, humans have been intrigued by the relationship between what we experience and the three-pound organ inside our skull. For thousands of years, injuries to the brain have provided us hard evidence that there is such a relationship and that it is multifaceted. Physicians since the time of Hippocrates have amassed such evidence, demonstrating that many different types of psychological processes are disturbed when the brain is injured.

The observations of Gall at the beginning of the 19th century triggered an innovation in studying the brain/ mind relationship: Gall attempted to correlate different sites of brain injury to differences in psychological profiles of the injured subjects. His correlations were crude: our high foreheads proclaimed the frontal lobes of the brain to be involved in our ability to speak. A patient with a cerebellar tumor had a history of having his sexual needs routinely satisfied by at least two women: ergo, it's sex and the cerebellum. These attempts at "localizing" faculties of mind within regions of the brain shortly led to phrenology: reading the bumps on the skull to indicate the size of the underlying brain region as indicating the development of a particular faculty. High forehead = language-based intelligence; a marked "inion," a bony ridge at the base of the back of the skull = sexiness. As I have noted earlier, Broca took off from these speculations to localize a language center in what is now called "Broca's area." William Uttal of the University of Hawaii has called the current readings of brain scans, such as fMRI, "the new phrenology."

Today, the fact that correlations can be made between various conscious psychological processes and brain function by way of brain-imaging procedures (PET and fMRI) is well established. These correlations have been viewed in a variety of ways. The most accepted way, adopted by most brain and behavioral scientists, is to affirm that psychological processes *emerge* from combinations of elementary brain cell activities, much as the liquidity of water, at ordinary temperatures, emerges from a combination of two gases, hydrogen and oxygen. Given this "emergence" view, we are led to explore various properties of brain cells and their combinations to see which combinations lead to which psychological "faculties," such as the ability to talk or make music. In this search we need to know the way in which the elementary properties of our brain cells bind together to *form* a psychological property in the same way that valences characterize the binding properties of oxygen and hydrogen to make water wet. The problem of specifying "valences" for combinations among brain cells to form behavioral traits is, however, a difficult one.

In science we recognize two types of emergence: one type claims that emergence occurs *when two or more properties of disparate substances combine in specific ways to form the properties of a new substance*. Occasionally this alternative has been become realized, at least in part, as in the periodic table of elements. However, scientists, more often than not, insist that such reduction has been attained when it is not— and that if it is not attained, then it certainly will be when more effort is expended. This attitude faces many problems.

The second type of emergence asks only that the *language* of several fields of inquiry be made compatible. This is a reasonable aim that is attainable in the brain and behavioral sciences. It provides an alternative to raw emergence that I'll take up shortly.

Psychological properties, especially those of conscious awareness, emerging from brain processes face a problem (called "supervenience"): How do the emergent properties influence the constituents from which they emerge? How do thinking and feeling influence the way the brain works? A tentative answer of sorts can be given by an analogy from other emergent instances: The liquidity of water at ordinary earth temperatures, and the fact that when it freezes into ice it floats, has redistributed oxygen and hydrogen on the earth's surface. The liquid water, by pooling in ocean basins, has taken oxygen and hydrogen out of the atmosphere and thus redistributed their location.

For psychological processes, the redistribution of components by the operation of their emergent is encapsulated in the slogan "The pen is mightier than the sword." Thoughts and ideas are powerful in changing the distribution of useful "brains" in the world, whether by outsourcing the development of computer programming or by velvet (bloodless) revolutions in Central Europe, such as those that occurred with the dissolution of the Soviet Empire.

One view that mind emerges from operations of the brain assumes that mind can be *reduced* to the way brain cells work. As I noted earlier, Francis Crick took an extreme stance of this view by suggesting that if we knew what every cell in the brain is doing, we could do away with mind as psychology altogether. This view would leave us with a totally material world-view in which we need not take responsibility for our actions. After all, when our actions are totally determined by the doings of the cells in our brains, those cells cannot be held accountable.

An, alternate, and more useful, starting point for inquiry can be the fact that *we* are asking the question "How does the brain work to enable conscious experience?" We start with our own conscious experience and the "phenomena" that compose it—in this case augmented by the cumulative experience of families and friends and teachers. We learn that there is a relationship between psychological processes and functioning—especially malfunctioning, injured—brains. We then explore the relationship and find out as much as we can about brain processes and their influence on conscious experience. In this view, the mind/brain relationship is often characterized as a gap: When we begin with our conscious experiences and try to relate different brain process to those experiences, we find that there appears to be a gap (technically called the Cartesian cut, which I will explore in Chapter 24) between our ineffable experiences and the processes going on in the material brain.

A rough metaphor helps me to understand what I am writing about. The wetware of my brain is operating while I write this paragraph. Coincidentally, so is the hardware of my computer. If I examine the various levels of programming, I find that binary, hexadecimal, low- and high-level operating systems, Java- and natural language-codes are all operating. I can obtain, for a moderate price, the *transformations* that lead from the binary operations of the computer hardware to my natural language, English. The transformations lead from the operations of the deep and surface processes of the brain to my natural language, English, the subject of the investigations described in this book. Note that what goes on in the computer at any moment does not change as a function of the level of coding which I am examining. The same is true of how my brain works: I can address my brain/mind research at various levels from synaptic membrane channels, the operations of the dendritic web, neural circuitry, brain systems analysis to behavioral, linguistic, conscious and social levels of inquiry. The workings of the brain remain the same through all these levels of analysis. What is gained is that with each transformation we achieve a substantial increase in understanding and in efficiency and effectiveness in navigating our world.

Currently, many brain/behavioral research endeavors do not try to bridge the gap between brain and mind by understanding the *how* of the relationship; rather they try just to *fill* the gap with correlations. Much of what I see happening currently is this *gap filling,* even though the scientists involved vow that they are searching for how psychological properties can be reduced to, or emerge from brain.

The ordinary ways to conceive of emergence and reduction as well as gap filling all have their limitations and are unsatisfactory because, for the most part, they lack any way to answer the "how" of the mind/brain relationship, the "particular go of it." Recently, as described in the previous chapter, an alternative to emergence and reduction has been developed.

## The Challenge

The issue raised by Toynbee's quotation that introduces this chapter describes a limitation in the very nature of today's conventional science as it is applied to the experience-behavior-brain interface. There is no question that "the hard or thick" sciences, as they are practiced, have proven to be efficient and effective. The effectiveness is in part due to the fact that, for the most part, scientists try to find direct causal relations among the observations they make. This works to some considerable extent: the bacterial and viral causes of disease and the causal effectiveness of immunization and medication are examples of what has come down to us through David Hume and British empiricism as Aristotle's "efficient causation."

However, when such relationships become more complex—as they do in the brain and behavioral sciences, as well as in thermodynamics and the communication sciences, or in quantum and cosmological physics—the explanations currently in vogue, based solely upon efficient causation, are stunted. In such circumstances Aristotle's other modes of causation, final and formal, become more relevant to understanding how processes relate to one another.

Final causation deals with teleology (*telos* = "ends") the purpose toward which a process aims; computer programming provides an instance of final causation. Formal causation encompasses both efficient and final causation; formal causation is invoked when an entire structure, a context, has to be taken into account in order to understand the relationships involved. Here I shall slightly modify Aristotle's terminology and use the term "formative causation" in keeping with the future-oriented theme of these chapters. My aim in this book is to show how substituting analyses based on formal, formative, rather than efficient causation can resolve many current perplexities in studying experience-behavior-brain relationships. Some practical examples will illustrate this approach.

When I examine the relationships among experience, behavior, and brain processes I am faced with a multiplicity of possible "causes". When the relationship between a brain process and what we experience and how we behave is closely knit, I note that the brain process "enables" that particular experience or that particular behavior. (In philosophical jargon, the relationship is termed essential but not sufficient.) Thus certain brain processes, as those of the cortical motor systems, *enable* skilled performances such as speaking or playing the piano. But just as important is the culture we grow up in and the invention of the piano, that *enable* the particular language in which we communicate and enable the performance of the concerto.

We often conflate what *we* do with what our *brains* do. Some scientists want to reduce our experience and our behavior solely to the workings of our brain. It is tempting to attribute someone's thoughts to "the way his brain is wired" or his outlandish behavior to "having a mixed-up brain." There is a basis for such reasoning: whatever we experience and how we behave at the moment has to be processed by our brain. But this answer excludes the broader reaches of causality: the immediate environmental triggers; the more extended influences on our brains by way of learning.

Today, the use of brain-imaging techniques has brought causation to the forefront of our attention. We find that a part of the brain "lights up" when the subject performs a given task. Many scientists and philosophers of science have concluded that the part of the brain so identified has genetically made possible the behavior of the subject. But we've also discovered that the patches that light up in the brain during imaging change in size and location as a function of learning. Therefore, neither the genetic nor the learning explanation by itself can be an adequate explanation of why this part of the brain lights up. Genes determine *possibilities*; experienced cultural input determines *the form, the formal structure of relationships* that these possibilities take.

For instance, I speak English; my colleague speaks Parsi. Both of us were endowed at birth with the capability for language, the capacity to speak. But which language we speak depends on the culture within which each of us was raised—as well as the culture within which each of us is communicating at the moment.

I was introduced to the issue of causation during the late 1930s, at the University of Chicago, by my undergraduate professor in physiology, Ralph Gerard. Gerard used to throw a piece of chalk at us students if he found that our reasoning was teleological—that is, if he saw that we were attempting to explain the occurrence of an event in terms of what it was "good for." Such teleological reasoning attributes an occurrence to what it achieves, not what has produced it. Gerard was correct within the context he was working in, but new ways of doing science have provided a wider context which embraces what Aristotle called "final causation." Indeed, today's computer programs are constructed teleologically—to perform what we *aim* to achieve. In a similar fashion, thermostats are "goal directed"—their purpose is to keep us comfortable.

Much of current science, and especially the brain and behavioral sciences, is wedded to discerning simple cause-effect relations. Thus, experiments are performed within the constraints of testing hypotheses: events are shown to depend on others that preceded them. As early as three centuries ago, David Hume had already pointed out that this type of causality can lead to false assumptions: his example was that just because a cock crows before the sun rises does not mean that the cock's crowing “causes” the sun to rise. The correlation between the cock’s crowing and the sun’s rising has to be understood within a larger context, a structure or “thesis” such as the Copernican understanding of the rotation of the earth. The correlation (crowing = rising) can be examined as a “hypo-thesis,” but this examination does not, of itself, test the direction of “efficient causation” in the relationship. Questions such as whether a particular musical performance is “caused” by a brain process, an inherited talent, by early exposure to classical European music, or by the availability of a musical instrument, appear rather silly when stated this way. Rather, the question that must be posed is: What are the step-by-step transformations that allow learning and instrumentation to modify innate brain processes to make possible the performance and appreciation of a concerto? The question is ubiquitous in biology: How does an acorn grow into an oak tree? How does the blastula made up of apparently uniform, undifferentiated cells mature into the person you fall in love with?

My aim in *The Form Within* has been to broaden the scope of explanation in the brain and behavioral sciences by selecting, *in addition to efficient and final causation*, still another arrow in Aristotle’s quiver of causalities: *formal* causation. As noted in Chapter 20, in the early part of the 20th century, Claude Lévi-Strauss, the famous French anthropologist, pointed out that if a system is simple enough, we can analyze it into its components and try to determine which component is causally responsible for an effect. But, when a system becomes complex—as, for example, language—we need to look at the formal, the formative, *relations between the processes* that compose the system.

## Archetypes

It has not always been this way. Over the centuries, form as shape and form as pattern have usually been juxtaposed, perhaps with one or the other the focus of discourse. As described in the Preface of this book, historically, form as pattern began to be seriously considered by Pythagoras who became concerned with *archetypes*. To review briefly: Archetypes originated as *tepos*, the Greek word for “patting, tapping, beating.” Tapping makes sounds. As early as 500 BC, Pythagoras began a scientific investigation noting the differences in sound made by a blacksmith beating on metal bars of different lengths. Pythagoras and the

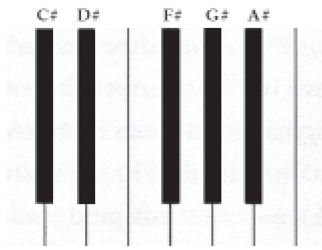
Pythagoreans augmented this observation by plucking strings of different lengths. The Pythagoreans visually observed the oscillations of the different lengths of strings and related them to perceived sounds.

Doubling the length of an oscillating string is heard as a sound that is an octave lower. The octave was so named because the change in sound could be related to ratios among the lengths of the strings. The frequency of oscillation of the plucked string was found to be proportional to the length of the string. For instance, if the lengths of the strings have a ratio of 3 to 2, the shorter one will be heard as being a fifth of an octave above the note of the longer. Eight notes were identified, the eighth being a repeat, an octave higher or lower than the first. Each note could be represented by a ratio of numbers.

Initially, the Pythagoreans were enchanted by the beauty and ubiquity of the patterns they had uncovered. But, as with so many regularities we find in nature, imprecisions arise when the range of observation is extended. In the case of the musical fifth, when it is repeated twelve times in ascending sequence, such a deviation occurs. It seems reasonable to expect that the sound heard would return to the original note, only eight octaves higher. Instead, when we repeat the fifth seven times, we find that we are off by an eighth of a note—forming an acoustical *spiral*. The discrepancy is called the "Pythagorean comma." An eighth of a note cannot be represented by a whole number, so the result is no longer a simple "ratio" and could therefore be described only as an "irrational" number.

The necessity for an irrational description of such a repetition was disturbing to the Pythagoreans. Nature could no longer be described in terms of ratios of integers and therefore seemed no longer rational or integral. But perhaps, by assigning the loss of integrity to the observer, the integrity of the rest of nature could be saved. In his book *The Myth of Invariance*, the mathematician Ernest McClain suggests that this attribution of loss of integrity to *ourselves,* as observers, formed the background for the ready acceptance of the concept of original sin.

Later, the acoustical spiral— a shape—was found to be generated by an archetypical self-organizing pattern: Fibonacci numbers are composed by adding each number to the one preceding: 1+1 = 2; 2+1 = 3; 3+2 = 5; 5+3 = 8; and so on. Botanists and painters have called the origin of such patterns the "golden mean" because they found them in plants and animals, such as the chamber of a nautilus shell. Fibonacci ratios describe all these natural forms.




*80.*

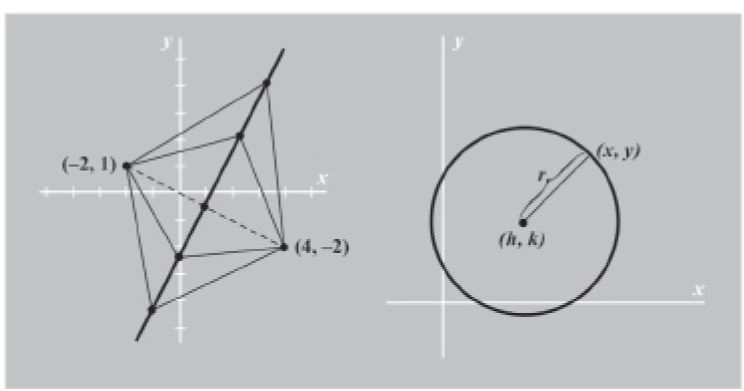

*81. Fibonacci Spirals as found in Nature*

In assigning numbers to shapes and to the results of observations, Pythagoras initiated the application of mathematics to give meaning to the results of observations. Currently we are witnessing a similar attempt to organize a comprehensive view of the cosmos according to string theory—the idea that minute subatomic vibrating strings are the elements that make up the universe. Pythagoras was the first to apply such scientific methods to relate our views, our observations, to physical measurements. These methods raised issues that had to be faced, issues that even today we tend to gloss over rather than to probe our profound ignorance.

# Viewpoints

In the 16th century, René Descartes based his division of matter from mind on the distinction between types of form: the shape of matter is geometric; thought is inherently patterned. But he did more: He invented a method by which geometry could be brought into correspondence with patterns—by letters representing numbers, that is, by algebra. He devised "Cartesian" *coordinates* that display the values of the relationships among numbers along their axes (ordinates and abscissas) and thus could plot these relationships within the field delineated by the axes as a line or a curve. *Inherent relationships could now be outlined*.

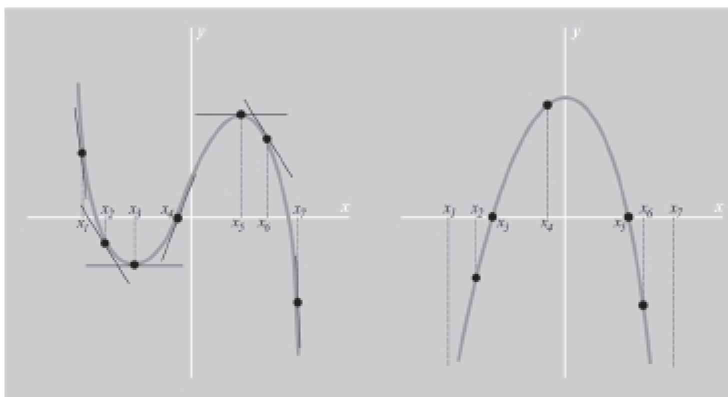
During the 17th century, Isaac Newton and Gottfried von Leibniz used Descartes's recently invented method of outlining inherent relationships among algebraic representations of numbers that we use today in analyzing the results of making electrical recordings from the brain. Newton and Leibniz showed that any curved shape, any surface, could serve to locate, in time and space, the observation being measured: location was defined as pattern—a point on the surface in its relation to its neighbors. In turn, the accuracy of the measurement was defined by the between-point-distance which can be varied according to the needs of the task: the smaller the distance, the more accurate the measurement. Points may be infinitesimally small. And when we sum up all the points and their relationships, we obtain a measure of the area or volume that is enclosed by the surface. Areas and volumes may be infinitely large.



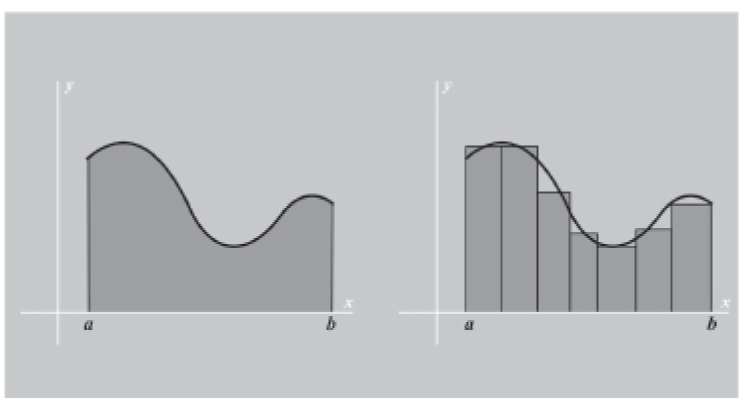

*82. Coordinates*

Leibniz wrote a book called *The Monodology* wherein he describes a world-view that centers on inherent relationships that are self-contained shapes, much like those Russian dolls that contain, within each, another doll and, within that one, another and another. For Leibniz, the most encompassing shape that contains "all" is Unity, that is, God.

When I first read *The Monodology* in my teens, it seemed to me that the aging Leibniz was simply making his peace with God, the ultimate monad. It was not until my own work led me to holography that I realized that Leibniz's monads were derived from his viewpoint that also generated his mathematics. Leibniz based his calculus on accurately measuring shapes; monads were conceived by him as *transformations*, shapes that encompassed each other to compose the world that we perceive. Every monad is a world apart that reflects the whole macrocosm; monads are "windowless," one contained within another, much as those Russian dolls. Today there are proposals concerning multiple universes that are essentially monadic in character.



*83. Derivative: Locating a Point on a Surface*




*84. Integration: Determining the Area of a Surface*

*Change "windowless" to "lens-less," and the structuring of the world we perceive is transformed not into shapes that contain one another but rather as holographic processes formed of interpenetrating patterns.*

Newton had to choose between explanations of his observations in terms of shapes and explanations in terms of patterns. In discussing his *experiments* with light, he chose shapes—points, particles—to describe his results, contrary to his contemporary, the Dutch physicist and astronomer, Christiaan Huygens, who described light in terms of patterns of oscillations. However, much of Newton's activities centered on alchemy, on patterns of relationships and their power to transform, which had initially been based on the oscillations that produce sound. Thus, when it came to *analyzing* patterns of color, he divided the spectrum into seven colors, explicitly in analogy to the seven tones of the dia-tonic scale.

## Action at a Distance

An essential issue where we need to distinguish pattern from shape concerns communication: How can a pattern generated in one location at one moment in time be sensed at another location at another time? For the Pythagoreans the question was: How do the patterns generated by oscillations, the vibrations of strings, reach the ear of the listener? Their answer, to which we still subscribe today, was that the air provides the medium for transmission, much as water serves as a medium for transmitting the energy that produces waves at a shore. But when we look closely at waves, they turn out to be rather mysterious: Swimming at the beach, one is bowled over by an incoming wave (unless we bodysurf or ride on a surfboard) that clearly moves the water. But get out beyond the breakers on a raft and all that happens to the raft is a bobbing up and down, an oscillation. The energy of tsunamis (more generally called "solitons") traverses the entire Pacific Ocean practically undetected, only to raise huge eighty-foot-high devastating moving walls of water on reaching the far shore.

Quantum physics has struggled for almost a century with the question: Do subatomic processes occur as particles or as waves? When measured at an aperture, a slit, the energy activates the measuring instrument discontinuously; when the energy hits the wall behind the slit, interference patterns produced by waves are demonstrated. So the question is: Does subatomic energy form things, particles, or does it come in waves? Or both? *Or neither?* If the energy is like that of a tsunami, it exists as oscillations until there is a shore, a measuring device to constrain it. The attributes of the shore, the context within which a measurement is made, configures the subatomic energy as much as does the energy itself. (See Appendix A.)

Patterns that produce change, measured as energy, can be transmitted across space and time. Ordinarily, transmission needs a medium within which to operate. When we cannot identify such a medium, we are puzzled and give the observed phenomenon of "action at a distance" a name. Newton used the name "gravitational force" for one such recurring action. Einstein suggested that the medium within which gravitational and other forces operate might be the *shape* of space-time itself. Over a prolonged period of usage, names appear to make palpable the observations they were invented to explain. But from time to time, on the basis of new observations, a re-examination of the ideas that gave rise to the names occurs. Such a re-examination has taken place in atomic physics and in cosmology over the past century. Currently (as suggested by Einstein in the quotation at the beginning of the next chapter) cosmologists are looking at *pattern* (e.g., oscillations of strings) rather than the shape of space-time as *the medium* within which actions and energy transmission can occur.

## The Power of Names

Newton could not formulate his science without resolving the transformative issues that alchemists had also faced. Initially, in his equations involving velocity, momentum and acceleration he successfully followed Galileo's hands-on way of proceeding. But in order to unify the Galilean observations with the observations of Tycho Brahe and Johannes Keppler on the motions of the planets, he unsuccessfully tried various explanations in terms of ethers of various densities. Much to his dismay, Newton had finally to resort to Keppler's invention of a "gravitational force," a Pythagorean "relationship" between centers of shapes, to account for action at a distance that could not be directly explored.

The gravitational relation is a *pattern* that gives *form* to our *observations*. Gravity is not a "thing," a shape that exists apart from our powers of observation. Newton had to ask, as do we, "Is the pattern of the relationship that is gravity due to the way the human sensory apparatus works?" And why today do we tend to "reify" gravity to be a shape, a thing rather than a relationship? A part of the answer lies in the human propensity for naming, thus *assigning an existence as a thing, an entity, to that which has been named*. This shift in meaning has consequences, as we saw in Chapter 8, when we tried to describe what we experience as a muscular force in terms of Newton's gravitational relationship.

An anecdote illuminates the issue. I've been puzzled by a question friends often ask me when I mention someone I've recently heard from or worked with in the past. My friends always persist by asking "Who was it?"—a question I could only answer to their satisfaction by coming up with a name—a demand rarely fulfilled, because I'm bad at recalling names. As noted in Chapter 20, I was discussing, with an undergraduate student majoring in philosophy, the fact that much of the central area of the human brain cortex of the left hemisphere is involved in naming, and I was wondering why this should be so important. The young lady promptly explained: "If something doesn't have a name, it doesn't exist." Conversely, if it does have a name, does "it" exist? From her comment, I suspect that Newton was upset when he realized that using the word "gravity" for a phenomenon that was, for him, an *intuition* he was naming, something he could not "lay his hands on" but which existed only by inference from measurements made of the patterns of relationship between shapes: planets and the sun; the sun, and its galaxy.

Today, Newton's gravity, an attraction between material shapes, has become familiar because we have learned from an early age that the named "it" exists. Now some additional observations in quantum physics and cosmology demand explanations of action at a distance, relationships for which we had to coin new names. "Fields," "forces" are the name most often applied to the patterns that relate material shapes into larger units in physics and cosmology. "Valence" is used in chemistry, as in H2O, where the two atoms of hydrogen have two negative valences and the atom of oxygen has two positive valences, thus allowing them to bond, to combine. In biology and psychology, we use the term "memory" to describe the bonds that bind patterns, bonds that describe processes occurring at one time and place with those occurring at another time and place. Naming is the most popular and useful way to identify observations, *provided that we* *do not lose sight of the fact that when we name a pattern we should not confuse that pattern with a shape just because it has a name.*

## The Birthing of Psychology as a Science

Names have played a critical role in forming the science of psychology as well as forming ideas in the natural sciences. B. F. Skinner was adamant in his insistence that behavioral science could never be based on the use of natural language. Noam Chomsky's devastating attack on Skinner's views did not change this. I heard that when Skinner read my paper "On the Neurology of Thinking," he was very upset, exclaiming: "Such beautiful data couched in such horrible language." But when it came to the relation between brain processing and behavior, Skinner made it clear that they were different: "There are two unavoidable gaps in the behavioral account, one between the inciting stimulus and the organism's response and the other between that response and its effect on further behavior. Only brain science can fill these gaps and in doing so it completes the account; it does not give a different account of the same thing."

Freud, also interested in creating a *science* of psychology, distinguished, on the one hand, between his clinical theory derived from his interviews with patients, and on the other, his metapsychology, which had two components: brain processes and cultural contingencies.

The critical role played by names in birthing the science of psychology is described in a superb book by Kurt Danziger *Naming the Mind: How Psychology Found Its Language* (1997). Danziger shows that many of the ideas, and therefore the names we use in psychological science, originated in sociology (and culture) and were modified on the basis of bias and experimental result to form the language by which we communicate today in psychology.

## Remembering

As described in the previous chapter, our remembrances, even more than our perceptions, undergo transformations as our brains process them whenever there is a change in the conditions of processing—such as a view from a different person's perspective or from the vantage of a new job or a new relationship. An often-used example is the story of

*Rashomon*, a Japanese movie from 1950 in which the same story is shown from numerous perspectives. Another, perhaps my favorite example, is Lawrence Durrell's 1957–1960 *The Alexandria Quartet*, a set of novels about the same group of people, each book narrated by a different member of the group. People exposed to the same situations "remember" them differently as each person views his group from an egocentric set of coordinates. These egocentric views are different from the view of the group from outside the group, a view in which the coordinates have a "heliocentric" origin.

Sir Frederic Bartlett of the University of Cambridge, England, called attention to the fallibility of memory in his memorable 1932 book *Remembering*. At a conference held at Cambridge University in the mid-1950s, I presented my ideas on "The Neurology of Thinking": I indicated that the brain's transactions with sensory input organized our attention; that the *brain's* transactions with its motor output organized our intentions, and that the *brain's* transactions with its memory organized our thinking. I emphasized that the transactions entailed transformations, transfer functions. But I did not, as yet, have clearly in mind the conception that correlations were inadequate to handle these transactions — that a change in coordinates, "coordination," characterized the transactions. Nonetheless, Sir Frederic expressed his approval: "Best thing I've heard since Lashley."

Furthermore, it would still be a decade before I could suggest how our sensory input, motor output and "thinking" might coordinate with our brain's memory processing. As described in earlier chapters, Leith's implementation of Gabor's holographic process finally indicated *how* the brain's memory could become distributed (*dis*-membered) before being assembled (*re*-membered) on any particular occasion. As noted in Chapter 2, on the basis of Leith's implementation, I was able to propose that two separate brain processes are involved in the organization of the memory process: a deep distributed structure that is made up of fine-fibered branches of brain cells along with their connections—a web of neuro-nodes; and a surface structure made up of neuronal circuits that is composed by large nerve trunks. Memory becomes distributed in the deep structure, where it can be influenced by local chemistry and/or new inputs from other parts of our brain as well as input from our senses and the response of those senses to our actions. Remembrances address the “content” of this distributed store, formulate and reformulate the retrieval according to the demands of the moment.

## The Roads Not Taken

The story of how I gradually arrived at my ideas about how memory becomes processed in the brain is worth telling because, for students especially, it shows how understanding is often so slowly achieved. To paraphrase William James, one must continually bring back a wandering attention to the issue at hand. Our journey is rarely straightforward.

The main obstacle to my understanding of how our brain organizes our memory was that I shared the commonly held conception that memory processing consisted of storage and retrieval. This obstacle was removed only when I realized what should have been obvious to me: that retrieval itself is a stored memory process—a memory process that is separate from, but addresses, the distributed memory processes in the deep structure of our brain. In the analogy I presented in Chapter 19, not only the performers in an orchestra, with the help of their musical scores, need to remember the music, but so also does the conductor, if he or she is to elicit the appropriate musical response from the orchestra. Memory “retrieval,” though separate from what I have called deep processing, is nonetheless a *stored* brain process that must become activated to be effective. Here is the story of my journey into “memory,” much as it happened.

## More on Lashley

As so often, my journey’s starting point involved my involvement with Karl Lashley. Lashley had always been deeply concerned with trying to decipher the *form* memory might take in our brain. In his research, he had injured large regions of the brains of rats, such as their visual cortex, without eliminating the rat’s visually guided behavior. Lashley had therefore concluded that our brain had within it great reserves for storing the results of learning, reserves that are mobilized when needed for remembering to occur. Indeed, as far as Lashley had been able to discern, memory appeared to be distributed widely over a mass of brain tissue.

Lashley had supported his conclusion with additional research, again using rats. He had trained them to carry out tasks such as running a maze.

He then endeavored to find the area of the rat's brain that "contained" the memory of what the rat had learned. He destroyed different areas of their brains, but no matter which part of the brain he did away with, as long as he left a small portion, the rat still retained the memory of what it had learned. Its skills might be seriously affected—the rat might stumble through the maze, for instance—but it still remembered the route it had previously learned in order to obtain a reward.

Lashley concluded that there was no specific location in the brain that held a specific memory, that each memory must become distributed throughout an entire region of the brain. Lashley summarized his results in his now-famous paper, "The Search for the Engram" (an engram is a memory trace). "I sometimes feel," he said, in reviewing the evidence on the localization of the memory trace, "that the necessary conclusion is that learning is not possible. Nevertheless, in spite of such evidence against it, learning does sometimes occur."

For the most part, psychologists were pleased to accept Lashley's views. Gary Boring, the Harvard historian of experimental psychology, commented that, in view of Lashley's findings, psychologists need not trouble themselves about brain anatomy or physiology since, in Lash-ley's terms, all parts of the brain have equal potentiality to learn. Of course, this was an extreme statement and over-simplification that Lashley himself did not believe: he had frequently stated to me that limited regions of the brain might be essential for learning or retention of a particular activity, but the parts within such regions appeared to him to be functionally equivalent. As he told me on several occasions, "It's important sometimes to state things in black and white or no one will listen. One can always retract in the next publication." Though he was indeed heard, I believe he frequently did his own ideas a disservice by overstating them.

On another occasion, after Lashley had given a fascinating talk on instinct—that is, inherited memory—he took a different tack. I asked him to define "instinct." My query brought forth more examples and stories, but no definition. When I kept pressing for a definition, Lashley finally said, "Dr. Pribram, in life one has a choice of being vague or being wrong. On this occasion I choose to be vague."

(We were Dr. Pribram and Dr. Lashley until his wife died in 1956. On that occasion, he wrote a lovely letter saying that I was the closest he had come to having a son and that we should address each other as Karl from then on.)

Lashley's answer was maddening to someone like me who, as I like to quote Clerk Maxwell, wants "to know the particular go of it." How can one know the how of a process with only anecdotes and a name to go on? In his over-statement of the case for a distributed memory and his under-statement of his views on instinct, Lashley fell heir to the Pythagorean propensity for relishing the mystical.

## A Different Road

My own clinical experience regarding the role of the brain in organizing memory differed from Lashley's. My view of memory storage came from my residency with Paul Bucy, who wrote an excellent chapter in Roy Grinker's 1943 text *Neurology* on how to find the location of "brain tumors" on the basis of their effects on memory. This view of the relationship between brain organization and memory was based on our findings in patients and was shared by most neurologists, neurosurgeons and neuroscientists at the time, and still is. For instance, deficiencies in remembering faces occur when there has been damage to one brain area, while deficiencies in remembering words occur with damage to a different area. According to this view of memory, our memories are stored in particular locations, or "modules" of the brain.

In addition, I had been taught during my internship with Bucy that electrical stimulation of certain places in the brain can produce remembered stories of the patient's experiences. I was so intrigued by these results that I was drawn into the practice of neurosurgery, only to be sorely disappointed: nothing of the sort ever happened in *my* surgery. Electrically stimulating the temporal lobes of my awake patient's brains (when this could be done without causing damage) produced no awareness of anything, no stories or even words.

Some years later I had the opportunity to ask Wilder Penfield, whose work had inspired me to try this with my patients, about my failure, and he replied, "How many epileptics do you operate on?" I replied, "None. I send them all to you as I don't have sufficient facilities to assure that the brain is kept moist during the long course of searching for an epileptic focus." (Drying of the brain would cause more scars and seizures.)

Penfield, surprised by my answer, told me that eliciting any memories by electrical stimulation works *only* in epileptics. He was unaware that everyone didn't know this, adding: "I wouldn't be operating on normal people, or stimulating their brains, would I?" I urged him to point this out in his papers, one of which I was about to publish. He did so and thereafter he always made it clear that his results had been obtained exclusively with patients who were suffering from epileptic seizures.

Some ten years later, at Yale, Penfield's experiments were repeated, using electrodes implanted in the area of the brain that Penfield had found electrically excitable so that the same stimulation could be repeated on several occasions. A surprising result was obtained: when the patient was primed by talking about his or her childhood, and then the brain was electrically stimulated, the patient would produce childhood memories; when the patient was primed with talks about current situations such as family relations, electrical stimulation of the brain would instead produce memories of current events. The location of the electrodes and the parameters of electrical stimulation were identical in each case, but the contents of the patient's recalled memories were different and depended on the context provided by the different contents of the priming sessions. Penfield's, Lashley's and Bucy's review of the observations showed that ordinary neurological and neurosurgical practice on the relationship between brain and memory needed sorting out —and my conversations with the protagonists of these various approaches to memory failed to be illuminating.

## My Interpretation

My explanation of Penfield's results focuses on the brain scar that produces the epilepsy. The scar tissue itself actually acts as a conduit for the electric current to assemble— to re-member, or re-collect—a distributed, dis-membered store. In the intact, non-epileptic brain, a similar localized process (a temporary dominant focus of activity) using the brain's neuronal circuitry would normally assemble a memory from its distributed store of neuro-nodes in the dendritic deep structure of the brain. Both Penfield's and Lashley's results are readily explained, as noted earlier, by the realization that memory is processed at two levels of brain anatomy and physiology: a surface structure made up of separate localizable neural circuits and a deep structure made up of a distributed web of neuro-nodes in the fine-fiber branches of brain cells within the circuits. Neither the surface nor the deep processing of memory "looks like" what we experience in remembering.

## In Summary

To return to the beginning of this chapter: I have outlined *how* mind-talk and brain-talk become related by way of transformations. Linguistic philosophers have stated that psychological processes and brain processes are simply two ways of conceptualizing a single process: we have "mind-talk" and "brain-talk." Around 1970, standing on the shoulders of their insight, I began to ask what that process might be. I started by suggesting that whatever that process is, it becomes *embodied* in our psychological experience and behavior and in the way the brain works. We are not just talking; the patterns that the language describes *reflect* the way in which the process actually works. I used music as an example. The patterns we appreciate as music can be performed by an orchestra, embedded in the grooves of a compact disc, or sung in the shower in early morning. The patterns are not just talk; they become embodied in a variety of media.

The embodiment does not have a spatial form. Rather, it is an embodiment of pattern. In this chapter I briefly related the history of the discovery of pattern: *pattagein*. The Pythagoreans showed that relations between sounds could be heard when strings of different lengths were tapped. The history of the development of mathematical relations among patterns has led to the current formulation of how complex forms are generated. This formulation allows a fresh view of the relationship between psychological and brain processes. Rather than rely on correlations that demand emergence of psychological properties from brain properties (and an attempt at reduction of the psychological to the brain properties) we search for a *change in the coordinates* (a search for the transfer functions) that describe the relationship. The reliance of efficient causation or final causation does not work. What does work is Aristotle's formal, formative causation that, in this instance, is formed by transformation.

# Applications

# Chapter 22
## Talk and Thought

Wherein the view of language as communication is supplemented by its even more ubiquitous use as a form of expression—and the view that thought is a form of virtual expression.

---

> *"I cannot do it. Yet I'll hammer it out.*
> *My brain I'll prove the female to my soul,*
> *My soul the father, and these two beget*
> *A generation of still breathing thoughts, . . .*
>
> —William Shakespeare; *Richard II,* Act V., Scene 5

> *But of all other stupendous inventions what sublimity of mind must have been his who conceived how to communicate his most secrete thoughts to any other person, though very far distant either in time or place, speaking with those who are in the Indies, speaking with those who are not yet born, nor shall be this thousand or ten thousand years? And with no greater difficulty than the various arrangement of two dozen little signs upon paper? Let this be the seal of all the admirable inventions of men.*
>
> —Galileo Galilei

## Of Monkeys, Gibbons and Great Apes

I set out to understand the manner in which the human brain regulates the body and its behavior. Language is central to such an understanding because our initial encounter with the importance of our brains comes from what brain-injured patients tell us. Despite this, most of my research was performed with monkeys—primates who don't talk. The reason that non-human primates were essential to this research is that brain injuries in humans are too messy to be of use in enabling us to systematize the relationship between brain damage and the behavior of the person who has sustained such damage. This situation has changed considerably since the advent of PET and fMRI imaging techniques.

I was successful in my work with monkeys because I love animals and they usually love me. But to participate in my research, the monkeys had to spend a part of their time in cages. Monkeys do not thrive when caged singly, so I saw to it that there were always at least two animals in a cage. When they were not being tested daily, they lived in a large compound with plenty of available outdoor space. Also, I introduced human surgical techniques and other caretaking innovations to provide them maximum cleanliness and comfort. I'd rather have just hugged the creatures, but rhesus monkeys are not very huggable due to their feisty nature, so attachments were not all that deep.

By contrast, gibbons (minor apes) are delightful. I once visited an island within Bermuda where a colleague, José Delgado, formerly at Yale and then at the University of Madrid, had gathered a large group of gibbons. A beautiful young gibbon lady took me by the hand and, chattering continuously, showed me around the island. Though we'd been together only a few hours, parting was traumatic for both of us—she threw her arms around me, would not let go, screamed and wailed. Jose was not pleased and chided me: experimenters should remain aloof.

I seriously considered purchasing some gibbons for pets. Instead, I purchased two of them—a blond female and a black male—for my Stanford laboratory. My graduate student Penny Patterson and I tested them in a variety of environments including a mirror test, in which they failed to recognize themselves, which according to the accepted view means that they do not have a sense of self. I don't believe this but have no evidence to support my disbelief. Gibbons, living in a mirrored environment, occupied our research interests until I purchased Koko, a baby gorilla from the San Francisco Zoo, for Penny to raise and to teach "language" skills. Her research with apes, which continues today, helped a bit to fill the gap left in my studies with non-speaking monkeys.

Teaching "language" to apes was attempted repeatedly at the Yerkes Laboratory of Primate Biology. I had become intimately involved when I succeeded Lashley as director. Cathy and Keith Hayes had raised a chimpanzee, Vicky, in their home and had tried to get her to vocalize with no real success. The few vocalizations—"food," "toilet," "shoes," which Cathy thought she could differentiate—were not sufficiently distinct for the rest of us to acknowledge.

Vicky was not the brightest of animals. A caged male chimpanzee used as a control on various tests routinely did better than Vicky. This may have been due to the fact that Vicky's mother had bashed the infant's skull against the cement wall of their cage whenever an attempt was made to separate Vicky from her mother. Lashley, who had little faith in the "language experiment," thought we should not waste our time using Vicky in more promising experiments and (rather gleefully) assigned Vicky to the Hayeses. To this day, I don't know how the Hayeses failed to find out about this early history of their ward.

By the time I took over the Laboratory, Vicky was at puberty and ready to be paired with a mate. I was going to refurbish a small cottage (that had been used by the Laboratory's caretakers) for a proper "home" for the pair. But fate intervened: About a week after Vicky and I were sharing a drink, each of us sipping simultaneously from the same glass with our own straws, Vicky suddenly came down with a high fever and died. Cathy was very upset, almost hysterical, as might be expected. But Vicky's death solved a lot of administrative problems that may have made Cathy feel that perhaps I was responsible for Vicky's death. Interestingly, no one at the Laboratory worried or inquired about my health—after all I'd been sharing a drink with Vicky a week earlier and she was suddenly dead from what appeared to be a brain infection!!

The first chimpanzee who was successfully taught to communicate using signs was Washoe at the University of Nevada. The brilliant breakthrough was made by Allen and Beatrix Gardner of the University of Nevada. (Bea had been a roommate at Yale of one of my graduate students.) The Gardners used the gestures of American Sign Language, thus bypassing the vocal chords. The Gardners raised Washoe in their home in Washoe County. I repeatedly visited Washoe during the 1960s. Washoe mastered about 300 signs.

By now, several major apes, like chimpanzees and gorillas, have been taught to use American Sign Language. They all can effectively use about 300 signs. They can string together three signs and use the ordering of those signs in conveying differences in meaning: “Penny hug Me” vs. “Me hug Penny.”

They can use words to lie; and then laugh when the experimenter finds out that she’s been had: Penny had lost her watch and asked Koko if she knew where it was. Koko signed “no” repeatedly during the day, only to hand Penny the watch at dinnertime, laughing uproariously.

Apes as well as porpoises, whales and sea otters— and grey parrots— can go to find an object near some other object that has been flagged by an experimenter using sign language.

Primates, including apes, have been taught to recognize numbers and to attach numbers to how many objects are in front of them. They can also push symbols displayed on a computer screen, resulting in the delivery of the symbol in an attached cup. The ape then accumulates the symbols in order to trade them for bananas, apples, oranges, peanuts, etc.

The most impressive of these results has come from Kanzi, a male bonobo (pygmy) chimpanzee at Georgia Tech. An unsuccessful attempt had been made to teach Kanzi’s mother to respond to spoken English by Duane and Sue Savage Rumbaugh. Kanzi grew up listening and observing the simultaneous presentations of words in sign and vocal language. One day, Kanzi took over and carried out the requests that the experimenter had spoken to his mother. Kanzi’s skills have been nurtured, and he is proficient in using a machine that takes tokens to deliver his daily rations of food.

I was leaving after a visit with Duane and Sue Rumbaugh and wanted something to take home with me, so I asked Kanzi for a “souvenir”—a word he had not heard before. I explained to him: “I am *leaving, going* home.” “Can Kanzi *give me* something to take home?” After a few repetitions, Kanzi went to a rock pile, took a rock in his right hand and another, larger, in his left. He placed the second rock on a fairly flat surface and smashed the first rock down on it. He gathered the pieces, examined them and threw them into a trash heap. He did this again, and on the third try, he straightened up, chest out, and came over to hand me beautifully formed flint-shaped stones! We hugged and I departed, gratefully.

There have been serious and rather vicious disagreements as to whether apes can be taught language. I have tried to arbitrate among my friends and colleagues—and in the process lost the upper half of the middle finger of my right hand! I was in Oklahoma, visiting Washoe. I was trying to persuade the University of Oklahoma administration to change Washoe's caging: the cage was made of extruded metal, which has very sharp edges. Perhaps Washoe was trying to show me how sharp those edges were, when she suddenly came from the rear of the cage while I was feeding her adopted infant (she had lost her own baby due to an infection that followed an injury to its finger that had been cut on the sharp caging) and slammed my hand down, cutting my finger to the bone. (Don Hebb had written a paper demonstrating that males always give a signal before they attack—while females never do.)

An artery spurted blood, and I made nasty remarks about trusting females. Washoe signed "sorry, sorry, sorry." My blood pressure fell to zero but I felt fine as we traveled into Oklahoma City to get to a hand surgeon who was too busy with office patients to deal with me. I was taken to the hospital and the surgeon operated on the hand beginning around 9:00 p.m.—some ten hours after the injury. The surgery was performed too late; gangrene set in after ten days and it took three further operations back at Stanford to eventually save the bottom half of my finger and rearrange tendons so my hand could function.

While I was recovering from surgery, I was able to dedicate the addition to the hospital—the purpose for which I had been invited to Oklahoma—with bottles of intravenous medication dripping into both my arms. I was able to attest to the excellent care I was receiving. Only an emergency message coming over the paging system for my host interrupted the smooth flow of my intravenous assisted presentation: his wife had suddenly gone into the last stage of labor and was delivering in the OB ward upstairs.

Neither Washoe's nor my ability to sign with our hands was impaired by the incident.

## Is It Language?

The battle over ape language was not the first to align those who wish to conceive of humans as distinct from other animals against those who believe in our more gradual evolution from primate ancestors. In the latter part of the 19th century, the French Academy of Sciences had to forbid discussion of the topic of the uniqueness of humans, because of the physical assaults that the Academicians lobbed against one another.

With regard to language, the issue is not that diffi-cult to resolve. Those who are raising apes to communicate with signs and symbols are doing just that: the apes use signs and symbols to communicate. However, this does not mean that apes use "language" as defined by the criteria of linguists: sentence construction, imbedding of phrases; flexibility in rearranging phrases, and the like. Apes don't communicate the way human Chinese, Arabs, Germans or Americans talk. Apes can be taught to use "words" to communicate, but concatenations of words do not meet the linguist's definition of language. And when apes feel that there are better ways to communicate, they don't bother with the words.

Penny Patterson, Koko the gorilla, my daughter Cynthia, and I were strolling together on the Stanford campus one morning. Flowers were in bloom. Penny wanted to show off Koko's talents: she signed to Koko to sign to Cynthia that she should smell the flowers. Koko understood and grabbed Cynthia by the nape of her neck and shoved her face into the nearby flowerbed. Instant communication. Who needs language or even words? Deeds are so much more direct.

## Complexity

Language is a prime example of a self-organizing system. Language begins as a proposition, a proposal by one human to another, a proposal for a possible action. In the few instances where a human has been raised in isolation very little emerges that can be recognized as language. Both during development and culturally, the language facility grows in complexity, not only as it is used to communicate with others but in self-communication.

But when we focus on language as *the* centerpiece of the difference between apes and humans, we are apt to miss the larger picture. In the opening chapter of this book, I noted the enormous difference between cave paintings and those made by chimpanzees. Nor do chimpanzees compose musical phrases. Nor do they pluck strings of different length and relate the changes in sound to octaves and their harmonics. No one has ever been able to train an ape to perform a finger-tapping sequence starting with the thumb, going to the index, then the middle, ring, and little fingers.

In brief, we can state that cortical *Homo sapiens sapiens* is more capable than any other animal of expressing and comprehending complexity. Complexity, as Lévi-Strauss noted, requires a formal rather than a reductive efficient-causal analysis.

For several years I criticized the use of the term "complexity" in scientific and philosophical discourse, because I could not understand the "how of it"—How can we measure it? The reason for my failure to understand was that I was thinking only in terms of *shape*: diversity and distinctiveness provide part, but only a part, of what makes a scene or a behavior complex. The French mathematician, Benoît Mandelbrot, has shown that progressive magnifications and "minifications" of a coastline produce as much diversity at each level as could be charted at the previous level. This is called "*self-similarity"* and is certainly *not* a measure of "non-similarity"—that is, of complexity, though it is usually referred to as such.

As described in Chapter 16, the answer to my quest to measure complexity came when I had to deal with complexity in the laboratory. Complexity can be measured in terms of *pattern*. I'll briefly review how the answer came about: For analyzing EEG recordings, I was provided the following recipe by Paul Rapp. Take each occurrence and give it a symbol. Then look for recurrence of groups of symbols and give each of those groups a new symbol. Continue the process until there are no more recurrences. The greater the number of levels of processing before there are no more recurrences of patterns, the greater the complexity, the greater the *refinement* of the process.

In Chapter 14, I dealt with the difference between information as a reduction of uncertainty and what I had called "novelty," the potential for increase in uncertainty. This insight had been attained while coming to terms with the function of the amygdala: processing the novelty of our experience is a change in what has become familiar; *novelty refines the familiar. Novelty produces an increase in the complexity of processing our experience—novelty is not a process of acquiring information in the sense* *of Shannon's reduction of uncertainty. Novelty is a function of amount of structure in redundancy, of recurrences, of repetitions.*

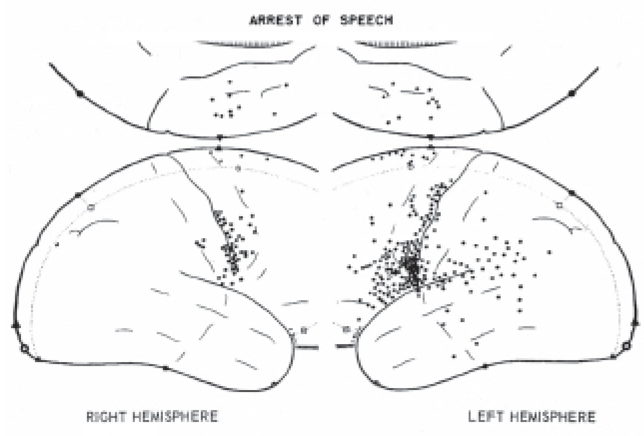
Now I had the opportunity to define complexity in terms of hierarchies of redundancy. It worked for EEGs: As we get older, our behavior slows down, but the patterns of our EEGs become more complex. The complexity, the refinement of our experience and behavior in all of their splendor is obvious. The relationship between our cultural complexity and the complexity of our brain's cortical processes is currently being documented daily by cognitive neuroscientists.

When it comes to the question of which brain processes make possible complex behavior, there are some answers that come easily and some that we have difficulty even in articulating. I'll take the easy issues first:

There is a large surface of cortex in the middle of the brain that we know has something to do with language. The particular method used to establish the relationship between this part of the cortex and language is to use brain electrical stimulation: A patient is asked to speak, the surgeon begins the electrical stimulation, and those brain sites where speech becomes interrupted are considered to be critical for speech. These electrical stimulations may also disrupt certain other movements, especially those involving the patient's face and fingers.

A more recent method of finding the areas of cortex involved in the production of language is to record from single cells or small groups of cells while the patient is speaking. Changes in the response of the cell indicate that the cell's activity is related to speaking. There is a good deal of congruity when we compare the results of the disruption of speech and the effects of its production on single cell recordings.

Currently, many laboratories use brain-imaging techniques to explore different aspects of understanding and producing language. Again, the parts of the brain that are activated lie in its mid-central region. These reports suggest that the cortical areas involved in language have a patchy (rather than a dense) involvement in any particular language function.




*85.*

The results of all of the experimental studies, together with reports of brain injuries that have affected speaking (aphasia), provide us with a general picture: in ordinary right-handed persons, involvement within the anterior regions of the left hemisphere relates to linguistic *expression*; the posterior regions are more involved in *comprehension*. The "typical" case of an expressive aphasia is a staccato of "content" words such as nouns and verbs, with very few "function" words such as "the," "and," "better," "less," and so forth. By contrast, the "typical" patient with a comprehension deficit will fluently rattle off sentence after sentence — performing so well that it may take the listener a few minutes to realize that the sentences are totally meaningless. It is this part of the brain that deals with the *semantics* of language.

Injuries near the "hand representation" in the cortex can lead to agraphia, an inability to write; injuries near the visual cortex in the back of the head can lead to alexia, the inability to read. These disruptions of language are often attributed to disruption of the large, long-fiber connections between cortical areas. In monkey experiments, I found that such long tracts are mostly inhibitory. Inhibition allows the local patterned processes in the neuro-nodal web to operate. No inhibition, no patterned processing.

Another observation about brain and language has been made: Injury to the right hemisphere of the brain in right-handed patients can lead to an inability to produce or to sense the intonations that are ordinarily a part of speaking. These changes in "prosody," as it is called, leave the patient speaking in monotone—or, if the damage is toward the back of the brain, unable to hear the nuances, the intonations that are often essential to grasping the meaning of a communication. When the damage is toward the front of the brain, the disability is in expressing that meaning in rhetoric, the *pragmatics* of language.

For years I worried about how pragmatic processing in the brain could be got together with those processing semantics, the referential "dictionary" use of language. My conclusion in several published papers was that the brain was not directly involved; that the person's culture formed the bridge between the meaning of an utterance and the effect it has on a listener. This conclusion is consonant with the way continental Europeans most often use the concept we call "behavior." In French *comportment* and in German *verhaltung* mean how one holds oneself. How one holds oneself with respect to—? With respect to the culture within which one is embedded.

But finally I came to realize that our motor cortex, in processing "images of achievement," does just such a "cultural" job, and the discovery of "mirror neurons" supports this conclusion. In language especially, as so often otherwise, the brain serves temporarily as the culture we navigate.

All the observations that I've briefly reviewed provide correlations; they give us only a first step towards understanding "how" language influences the operations of our brain, or how the brain's operations help to organize our language. Even at a gross level there has been an argument about Noam Chomsky's famous claim that we must have a separate "language organ" in the brain, an organ apart from the brain's more general cognitive facilitation. Of course Chomsky is right: there are individuals who are cognitively feeble minded, but whose speech is unimpaired. And vice-versa. But the "organ" is not a single lump of tissue: it is most likely distributed among other cognitive "organs," much as the Islands of Langerhans that control sugar metabolism are distributed throughout the pancreas.

Correlations, though a useful first step in helping us come to grips with a complex topic, do not address language in terms of the central theme of this book: *How does the form, the pattern, of a language become transformed into a brain process—and how does the form, the pattern of a brain process, become transformed into a language?*

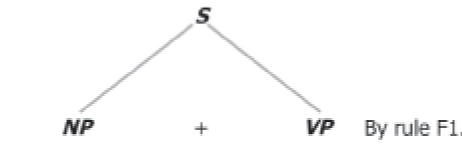
## Neural Networks and Neuro-Nodal Webs

Considerable progress has been made in studying this issue in the computational sciences. Massively connected artificial neural networks have been taught to produce language. The process has been slow, requiring large computers and huge amounts of processing time—sometimes weeks—to produce understandable words and phrases. But that is faster than it takes a human baby to learn a language.

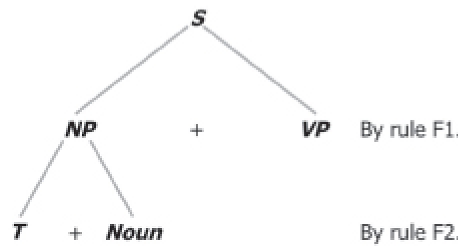
The reward of pursuing this exercise is that the course of development of neural network language acquisition has been shown to be similar to the course of development of language acquisition shown by babies: babbling, grouping of phonemes, construction of syllables, etc. All this is achieved without making up any symbolic representations during the course of language acquisition.

The success of using artificial neural networks in language acquisition points to an often-ignored aspect of the relationship between brain processes and speaking. Those of us who speak more than one language do not have to translate from one language to another when we think, write or talk. Each language addresses some deeper process that is "language neutral"—and this neutrality is not given in the form of visual pictures. Rather, this ultra-deep structure is likely to be akin to the dendritic fine-fibered web of neuro-nodes in our brain, the very web upon which the architecture of artificial neural networks has been based.

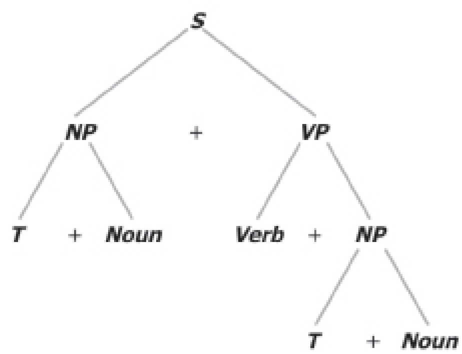
But of course, human languages do use signs and symbols—and most computer programming is based on symbolic processing. There is still somewhat of a gap in our understanding of the operations of artificial neural networks and our understanding of the "intelligence" of ordinary symbol-based computer programming.




First step in the formation of a sentence




The result of two steps in the formation of a sentence




Analysis of a sentence into its immediate constituents

*86.*

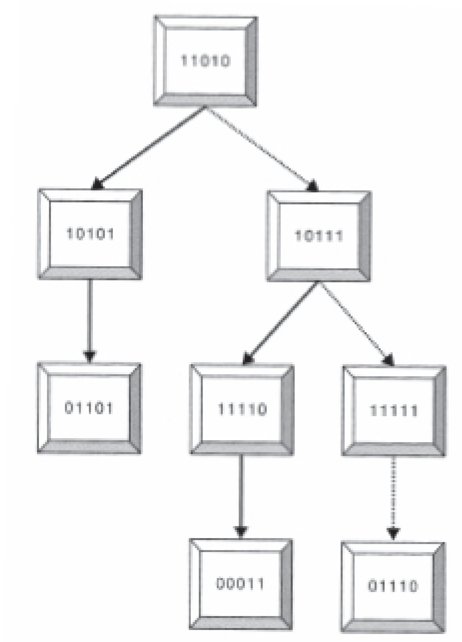
Gary Marcus, in his book, *The Algebraic Mind*, provides a method through which we can begin to fill this gap between pre-symbolic and symbolic processes. Symbolic processes are hierarchically complex structures in the sense that I defined above. Human language is characterized by a *hierarchy of tree-structures* such as those my co-authors and I described in *Plans and the Structure of Behavior*. But the neuro-nodal web, like the brain's dendritic neuro-nodal deep structure, is massively *parallel*. Marcus suggests that the transformations between these parallel and hierarchical structures may be performed by way of "treelets": hierarchies that are limited in depth, thus less complex than a fully formed symbolic process.

These treelets, *distributed in parallel over the processing medium*, are composed of "registers" that store "values of variables." In *Plans and the*

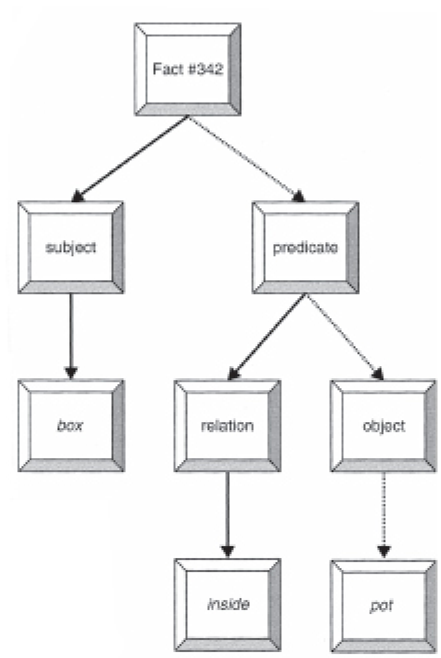
*Structure of Behavior* and again in *Languages of the Brain,* I called such registers "tests" which registered the degree of match of the pattern of a sensory input to a familiar pattern. When the registers become sensitive to a "bias," that is, a parallel way to alter the register, the bias establishes a value against which the tests are run. What I am suggesting is a parallel structure even *within* tree-lets as well as between them. Treelets become considerably enriched by this addition.

Marcus proposes that the variables stored in treelets provide the *meanings* of communications: propositions and sentences. In Chapter 16 I developed the proposal that we value an act on the basis of its utility in satisfying our desires. The utility of a speech act is its meaning. I'll have more to say about the structure of meanings shortly, and again in Chapter 25.

The meanings of spoken utterances, their value, are often enhanced by the inflections and gestures we use in parallel to the spoken word. Inflections emphasize a particular expression; gestures reflect its novelty or familiarity. The procedures developed in the practice of neurolinguistics provide a technique to assess the sensory modality used to provide such enhancement: We record the number of modality- specific words a speaker uses. Does the speaker mostly use visual similes, kinesthetic (muscle-related) words and gestures, or those derived from music or sound (auditory)? When I was tested using this technique, I was surprised to find out that I was using the kinesthetic mode much more often than I was using the visual; until then, I had thought of myself as a visual thinker.




*87. Treelet showing numeric registers*



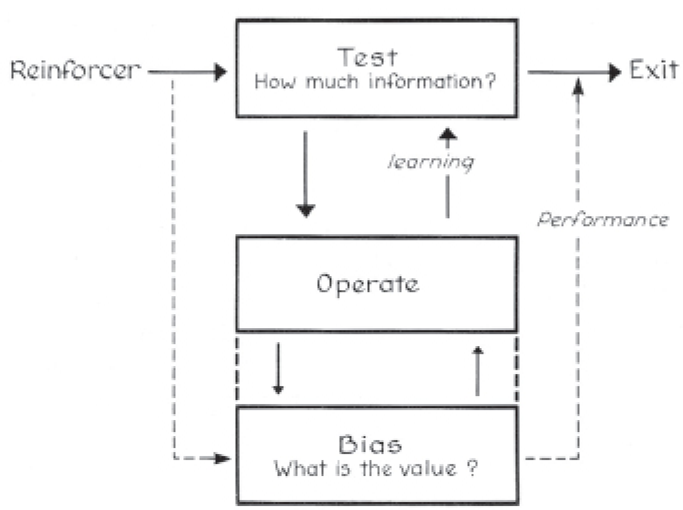

*88. Treelet showing names in registers (From* The Algebraic Mind*)*

# The Unfathomable

For many of the foregoing observations, we are able to ask questions and, in some cases, we can also answer them. But what follows are some observations that, so far, have eluded even letting us frame them into questions: A young professor of psychology has a reading problem following an accident. He can write but can't read his own writing. He can read numbers, even when they are interposed in "unreadable" sentences, but he cannot identify a letter when it is interposed among numbers.

Even more fascinating are the performances of the specially gifted: I mentioned before that I had the experience of watching a six-year-old girl listen to a piano sonata—once. She then played the sonata from memory—beautifully, with feeling. A classmate of mine at the University of Chicago was able to visualize any page from our 800-page textbook of medicine—at will—and "read" it to us (very helpful on exams). Thomas Edison is said to have been able to memorize an entire book in this fashion. Some cognitively-impaired persons can do multiplications of three- or four-digit numbers by other three- or four-digit numbers faster than a computer can kick out the answers.

People with these abilities are called "savants." Sometimes, when their general cognitive abilities are severely restricted, they are "idiot savants." More often they are normal cognitively and in every other respect. We know from our own everyday experience that talents are not equally distributed among us. We are taught to "Know Thyself"—find out what we are good at, or even better at than most people. But right now, in the brain sciences, we do not yet know where or how to look for what provides humans with our talents. Is it chemistry, brain circuitry, density of connections and/or very, very early experience?




*89. Valuing information (From Pribram,* Languages of the Brain*, 1971)*

## How We Use Language

Most obviously, language serves us in communicating. But the importance of naming in constructing "things"—recall my student's comment "if it doesn't have a name, it doesn't exist"—indicates that language must have other important uses. Language is a cultural creation and as such (as with other cultural creations) is self-organizing: plant a kernel, it branches and flowers. Dialects develop that help organize and locate social groups. This happens not only in native cultures but also among teen-agers and even within experimental laboratories: we develop a jargon, a shorthand way of talking about our observations, a jargon that has to be decoded before submitting a manuscript for possible publication.

In trans-disciplinary studies such as mine, difficul-ties are encountered unless the results are formulated; that is, given in the *form* required by one particular discipline. For example, I used brain recordings obtained while a rat's whiskers were stimulated to show what the range of Gabor-like cortical maps looked like. The community of "whisker-stimulaters" repeatedly rejected my manuscript because the problems they addressed were different, and they had never encountered Gabor functions. Only when a new journal was founded for the purpose of publishing such trans-disciplinary studies did the paper finally come to publication. I had sent it to the editor to find out only whether the journal might be interested—and was surprised by having it scheduled as the first paper in the first volume of the journal.

At a conference in Prague, my then Stanford colleague Bill Estes and I were asked to summarize the contributions made by psychologists in a variety of disciplines ranging from learning theorists to developmental to social and school psychologists. To Bill and me it seemed, at first, to be a welter of unrelated presentations—until we hit upon a way of organizing them. The presenters were all psychologists, so we asked ourselves: What were the questions each was addressing? It turned out that only about a half-dozen questions had been addressed, and we found that we could organize all the presentations around these questions. Each *presentation* had been formulated in the jargon of the subfield of psychology that was *re-presented*. By asking what the underlying questions were, we could *re-formulate* these earlier representations.

Language formulates our experience within the values of what we are familiar with. In order to more broadly communicate, we had to reformulate the essences of the presentations into a less refined, less complex set of tree-lets—and we discovered that framing questions within the broader, less specialized context of “psychology” served this purpose.

Another aspect of language is that it allows us personal expression or, as one of my colleagues described talks that were being presented at conferences, “station identification.” This aspect of our speaking can sometimes get out of hand, especially when the presentation is read from a written manuscript. Unless crafted by a novelist or author of an epic, the style of the written word is often more amenable to providing a recorded memory of a set of transactions than to serving as a vehicle for communication.

Alexander Romanovich Luria was chairing a session on frontal lobe function at the 1968 International Psychological Conference in Moscow. One of his students presented some of the work going on in Luria’s laboratory. We had carefully rehearsed her talk so that she could finish her presentation in the allotted twenty minutes. Of course, when it comes to the actual presentation, it almost always takes longer than planned. At the appropriate moment, Luria held up a large placard meant to give his student a five-minute warning to signal that her time was almost up. She ignored this signal and went on with her planned presentation. Luria then gave her a similar two-minute signal and another when her time was up. She kept right on with her presentation. After another few minutes, Luria went up to the podium and took her arm, but she continued talking. Luria led her off the podium, down to her seat—where she blithely continued until she had reached the end of what she had prepared. During our subsequent meetings, she good-humoredly laughed at what had happened and told me that she no longer has such difficulties in presenting her work.

This retreat into the cocoon of one’s personal, rather than inter-personal use of language occurs especially under conditions of stress in facing an audience. That is why most people at conferences read a prepared speech and/or heavily depend on visual presentations of what they have written. Early on in my career, I had to face similar stressful situations and used a variety of ploys to pull myself out of such a non-communicating use of language. On one occasion I had *written* my speech—something I rarely do—because I felt intimidated by the audience I was to face. I went up to the podium to make the presentation and found that I couldn’t read what I had written; my sight was blurred. I simply told the audience what was happening which served as my station identification, and went on to verbally *communicate* the results of my experiments.

The self-expressive use of language is much more common than we usually realize. This use of language helps us to sharpen and refine our thinking. The people who are the recipients of our verbosity serve as a whetstone against which we can hone the self-organizing aspects of our existence. Teachers do this. The presenters at conferences do this. Talkers on telephones do this. Dinner conversational-ists do this. Cocktail party guests do this. Sometimes these self-revelations are exciting and interesting to the listeners; sometimes they are boring. It depends on the interest the listener has in the speaker and the subject of that speaker's interests. In speaking, language is much more often used in this fashion than for the purpose of communication—and that is one of the important reasons why human language differs so profoundly from animal communication.

## Writing and Reading

As indicated in the opening quotation from Galileo, it is in the invention of writing and the reading of writings that the full measure of the communicative aspects of language come to the fore. The role of language in the development of meaning, by exploring contexts, that is, by reducing uncertainty and enhancing novelty, comes into its own by way of writing and reading. But even while reading, expression of one's thoughts comes into play: one imagines oneself in a participatory role as actor or listener while writing and reading.

## Thinking

By what process can thoughts influence a brain? Thoughts do not do so immediately. Rather, for a time at least, conscious thinking appears to be what philosophers call an epiphenomenon. Conscious thought is coincident with the activity of the brain but ordinarily does not influence the brain or the rest of our material universe directly. "They" can't put us in jail for what "we" think as long as we don't express those thoughts verbally or otherwise.

However, *that same activity of the brain that produced the thought can also influence other activities in the brain if the activity lasts long* *enough*. Such influences, such "temporary dominant foci of activity" as they are called, were shown to produce changes in Pavlovian conditional behavior: A dog was conditioned to raise his *right foreleg* whenever a certain tone was sounded. Then the motor region in the right hemisphere of the dog's brain was exposed and the region of the brain controlling his *left hindleg* was chemically stimulated. Now, whenever the tone was sounded, the dog raised his *left hindleg*. After the chemical stimulation had worn off, sounding the tone again elicited the raising of the dog's *right foreleg*.

A thought, conscious or unconscious, occurs and, *coincident* with it, there occur many other changes in the organization of the rest of the brain produced by changes in body functions. *These changes in brain organization are not immediately related to the occurrence of the thought*. They may be due to digesting the meal you had for dinner or the movie you have just viewed. As long as the two processes, thought and incidental brain organization, last long enough together, a correlation can become established. I have called this process a "temporal hold." The incidental change of brain organization can now further influence the body and its sensory receptors and concurrent actions. In turn, these changes in the body can change the brain, its memory. The new configuration can produce and be coincident with new thoughts, perceptions and attitudes though they may have only a tenuous connection to the original thought. Whenever we attend or intend, we use our body responses to *transform* the thought "into practical relations with the world we navigate." The transformation may or may not be an appropriate one!

Anyone who has tried to write can attest to the difficulty in putting what we think we know into a communicable form. The thought process is not imaging or verbalizing. Rather, thinking is an uncertain *groping* toward a more-orless well-defined target. Most of our thinking is, therefore, more unconscious and preconscious than conscious. Once we consciously formulate the thought into an image or verbal statement, the temporary dominant focus has had its effect and we test our "vision" or our "proposition" in the world we navigate—with the resultant confirmation or change in the thought. I am doing this right now: looking on the computer screen at the typed version of my thinking —confirming and correcting what I have written by way of ordinary perceptions and actions. But tonight at midnight I may wake up, realizing that I had left out something, worrying the thought, finally composing a paragraph—none of which has a direct effect other than by way of changes that have occurred in my brain's dominant focus, which most likely take place during rapid eye movement (REM) sleep. Thus the more encompassing reorganization of my brain occurs through its regulation of my body.

# Some Experiments

During the 1990s, John Chapin and Miguel Nicolelis at Duke University carried the "temporary dominant focus" type of experiment much further. First with rats and then with monkeys, they trained the animals to press a lever to obtain a drink of water. Meanwhile, they were monitoring cortical activity with electrodes implanted in the animals' brains. As reported in the February 2004 issue of *Popular Science*,

> *. . . what they [Chapin and Nicolelis] discovered instantly challenged the conventional wisdom on the way neurons send their messages. What they found was that the commands for even the simplest movements—required far more than just a tiny cluster of neurons. In fact a whole orchestra of neurons scattered across the brain—behaved like an orchestra. Beethoven's* Fifth Symphony *and Gershwin's* Rhapsody in Blue *sound nothing alike even if many of the same musicians are playing both pieces, on many of the same instruments, using the same notes. Likewise many of the same neurons, it turned out, participated in generating different kinds of body movements.*

Discovery often rewards the prepared mind. Chap-in, Nicolelis and I had discussed some of their earlier experimental results and mine: we were always "on the same wavelength." Their finding of "an orchestra of neurons scattered across the brain"—neurons that were involved in an act being analogous to the way music is produced—fits the findings I described in Chapter 8 on "Means to Action."

Chapin and Nicolelis took their experiments a most significant step further. They disconnected the lever the animal had pressed to obtain a drink and provided a drink of water to the monkey whenever his brain pattern signaled his intention to make the movement. The monkey continued to produce the same brain pattern as when he had actually pressed the lever, despite the lack of any correlation between external movement of his arm and receiving a drink. The cortical brain pattern represented the monkey's "image of achievement," the "target" of his action, not any specific movement to achieve that target.

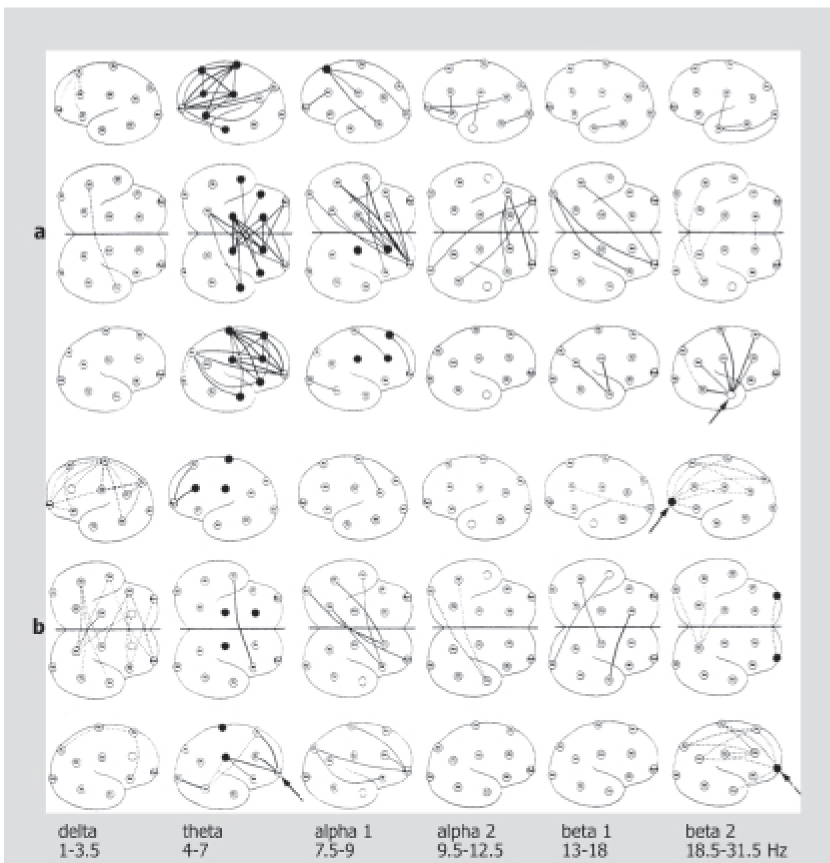
In another step, they used human subjects who had lost an arm. The subjects watched a display on a computer screen that was hooked up to a lever in such a way that certain patterns on the screen were coordinated with movements of the lever. The experimenters recorded the brain electrical patterns from the subjects while they were learning which patterns were correlated with the movements of the lever. The lever was then disconnected from the display. The display was now hooked up to another lever, a prosthetic arm. The display controlled the prosthesis while the subjects continued to learn which display patterns were correlated with what movements of the prosthesis. Finally, the computer display was turned off. With some considerable effort, the subjects learned to control some simple movements of the prosthesis with brain signals only. The visual input from the computer screen had elicited a brain pattern that was coordinate with "thinking of moving the prosthesis" and this was enough to accomplish the task. Trying to move a phantom arm and looking at the prosthesis became unnecessary: the brain pattern was sufficient to control the prosthesis.

The procedures Chapin and Nicolelis developed are akin to the research of those earlier experiments that established a temporary dominant focus of electrical excitation in an animal's cortex. The brain focus of electrical excitation takes control of the behavior of a paw or a prosthesis. In place of the chemical stimulus used in the earlier experiments, in the current situation the visual input from the computer screen serves to establish a much more refined, complex brain pattern through learning. As described in the quotation above, the brain pattern itself then "orchestrates" the operation of the prosthesis. The analogy with the production of music is well taken.

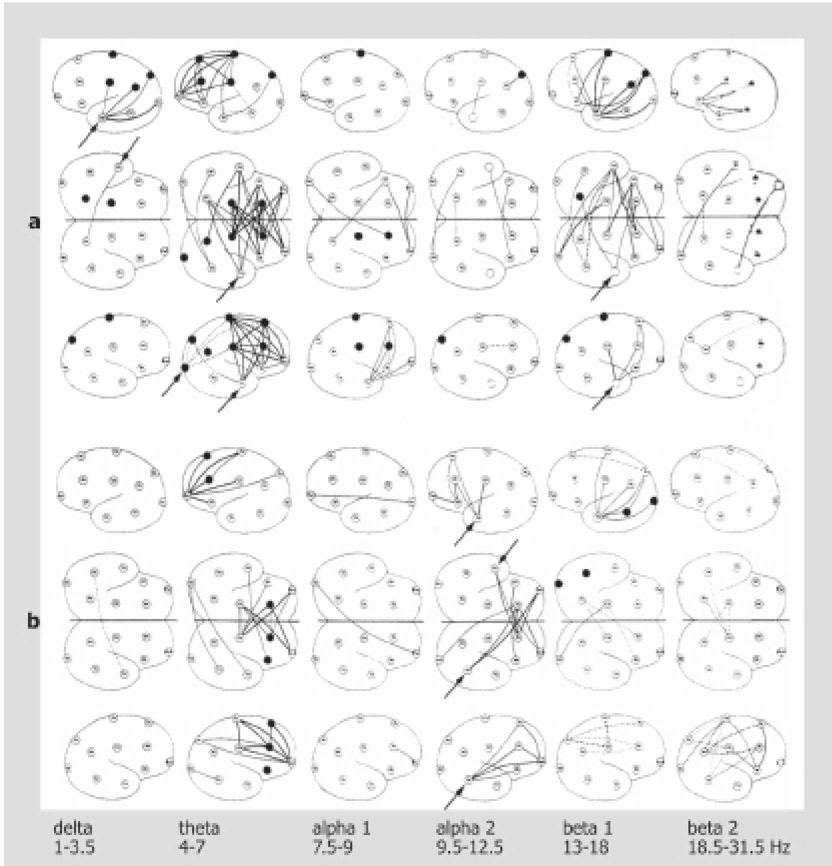
## Brain Electrical Patterns: The EEG

In fact, Hellmuth Petsche and Susan Etlinger of the University of Vienna have made electrical recordings (EEGs) from the scalps of humans while they were listening to music. Appropriately, these experiments were carried out in Vienna, for centuries a most famous music capital of the Western world. The patterns shown in each of these recordings differ according to the music the person is listening to: Mozart, Bach, Beethoven, Schoenberg and jazz each elicited recognizable differences in the recorded patterns.

Petsche and Etlinger then went on to ask whether such differences also appeared in trained musicians while they were reading a musical score, while they were remembering the music, or while composing. In each case, the differences between the brain patterns reflected the type of music being experienced or thought about. Recognizably different brain patterns accompany imagining, and thinking about, different types of music.



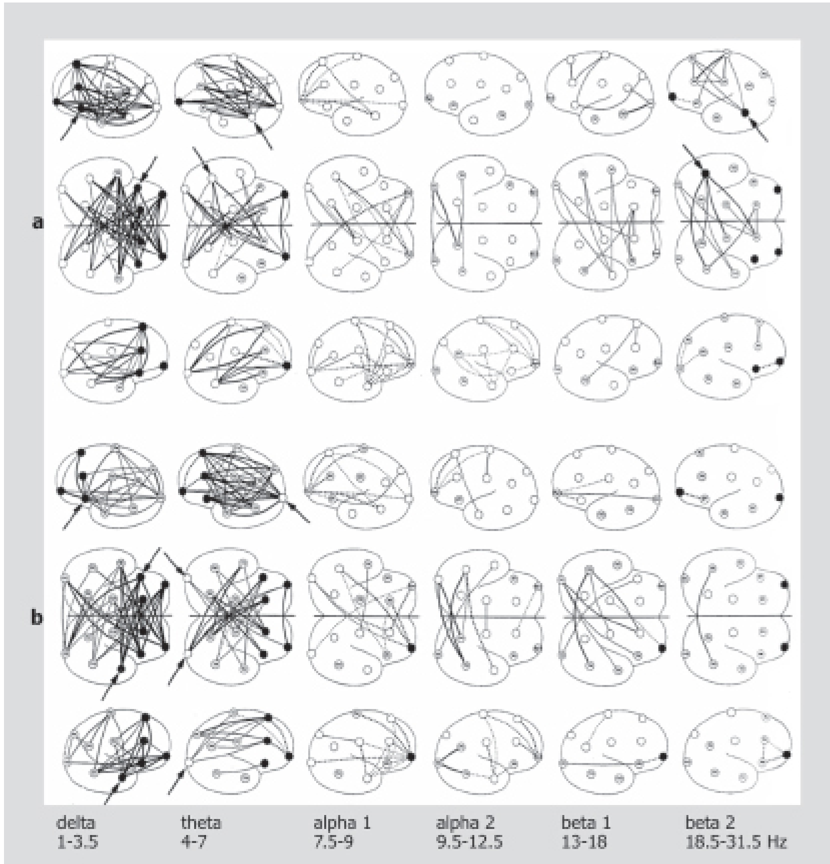

*90. Listening to Bach (a) vs. listening to Beethoven (b). (From Petsche and Etlinger)*




*91. Listening to Schoenberg (a) vs. listening to Jazz (b). (From Petsche and Etlinger)*

The fascinating results of these experiments remind me that Beethoven created his last quartets and his Ninth Symphony after he had become totally deaf. Would that we had records of his brain electrical activity during those creative moments!

Petsche and Etlinger also tested persons who spoke several languages. These experiments revealed that speaking different languages is also coordinate with different brain patterns. In addition, they showed that translating from one language to another produces different patterns from those that accompany translating from the second language to the first. Finally, they showed differences in EEG coherence patterns when a person is imagining an object from when she is creating a text—both with eyes closed.




*92. Imagining an abstract object (a) vs. creating a text. (From Petsche and Etlinger)*

In short, these investigations have identified differences in brain patterns that accompany differences in thinking. One can understand how scientists and philosophers might be tempted to declare, “If we knew what every neuron is doing, we could dispense with studying behavior and experience.” Or, in a somewhat more sophisticated approach, brain patterns and “thinking,” currently loosely described as “information processing,” are in some sense “identical.” Certainly, in everyday speech, we refer to a musical score as “the music”—as in “Where did I put that music?” So we tend to blur the distinction between a blueprint and the building it represents.

But, of course, closer examination shows that the *patterns embodied in the EEG, or the patterns embodied in a musical score, or the patterns embodied in speech are not identical*. The patterns can be correlated with one another, but if we want to know *how* they are related we need to know how one pattern can become *trans-formed* into the other: Transformations between patterns go beyond correlation in the sense that transformation poses the ”how” question: What are the transformations, the transfer functions, that enable such correlations to occur? Chapter 20 is devoted to explaining in more detail what is involved in the process of transformation.

## Deep Thought

*Language is a great aid to thinking, but language or music or pictures are not, in themselves, thought. We are often aided in thinking by language, music and pictures, but these aids are not the essence of thinking per se. As in the case of language, there is a surface and a deep structure to thinking. The surface structure leads directly to language and to other forms of experience, communication and expression of a thought. The deeper form of the thought process is like the ultra-deep form of language. As noted, multi-language speakers and mathematicians address this ultra-deep structure that becomes transformed during overt thinking and communicating.*

The experiments that led to our understanding of this deep structure of thinking were performed in the mid- 19th century in Würtzberg, Germany. The experimenters posed a well-articulated question to a group of subjects. The experimenters assured themselves that each person in the group had thoroughly grasped the meaning of the problem in question. The subjects were sent away with the instruction that they were to record the thought process by which they solved the problem that had been posed by the question. When the subjects returned to the laboratory, they had all solved the problem and had recorded the thought process by which they had arrived at the problem’s solution.

The experimenters were able to reach two clear conclusions from the results: 1) If a problem is thoroughly understood, the answer is already given in the question! All of the subjects had reached exactly the same answer to the question; 2) The course of thinking the problem through to an answer to the question was radically different for each person! Some of the subjects went to bed after thinking for a while and awakened with a well-formed answer. Others recorded a step-by-step procedure in coming to a solution. The thinking process of most of the subjects had taken some haphazard, but individually unique, course in between these two extremes.

Psychologists and philosophers were intrigued by these results. The most prominent among them were Harvard's William James and the University of Vienna's Franz Brentano. Brentano was Freud's teacher. Freud developed a technique to unveil the hidden differences in thinking-through a problem. He called the technique "free association." His patients came to him with a problem. By asking the patient to ruminate about whatever came to mind, Freud felt that he could retrieve the articulation of the question that formed the root of the problem. The brain's memory-motive and memory-emotive structures would make such "retrofitting" and "reverse engineering" of conscious from unconscious processes possible.

The form of the fine-fibered distributed web of the brain makes it likely that the form of the ultra-deep structure of thinking is a holographic-like distributed process. Dreams attest to such a possibility. Remembered dreams were called "compromise processes" by Freud because they partake of some of the structure of the waking state. But even in remembered dreams, uncles and aunts and children and places and things are connected up in a haphazard fashion, as if they had been entangled in another state during sleep. According to the reasoning proposed in this book, the potential of the ultra-deep structure of thinking is realized when the holographic distributed process becomes transformed by way of the memory-motive and memory-emotive processes into cortically engendered complex verbal and nonverbal language and language-like cultural forms.

## Highlights in Forming Talk and Thought

I'll recapitulate some of the more important and often overlooked insights reviewed in this chapter:

1. Fluent multilingual speakers do not translate from one language to another, nor do they have recourse to pictures when they speak. This indicates that there is an ultra-deep structure which underlies language, a structure that can become expressed in the variety of culturally formed specific languages. This ultra-deep structure is most likely processed in the neuro-nodal fine-fibered web of our brains.

2. The structure of language is made up of hierarchical treelets that operate in parallel. The treelets themselves function as biased homeostats that register the set-points attained from parallel inputs. Treelets account for what linguists refer to as a surface and deep structure of language.
3. Language is a self-organizing system that continually increases in complexity —though there are occasions when language is pruned in order to reach clarity of expression.
4. Language is as often used to hone self-expression as it is used for communication. Listeners should be aware of this and not lose patience.
5. The invention of writing and the reading of writing have extended the reach of language beyond the here and now and beyond small cultural groups —the first successful attempt at globalization.
6. The brain processes underlying thinking are akin to the ultra-deep structure of language but encompass other cultural expressions, such as those that give rise to music, painting and the creation of artifacts.
7. Thinking influences brain processes by way of a “temporal hold” during which temporary dominant foci occur in the brain that alter functions of parts of the body (including the sense organs), alterations that, in turn, change brain processes.

# Chapter 23
## Consciousness

Wherein I explore our brain's role in forming the multifaceted aspects of the impressions that we experience—and their unconscious underpinnings.

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> *. . . [A]ll original discoveries and inventions and musical and poetical compositions are the result of proleptic thought—the anticipation, by means of a suspension of time, of a result that could not have been arrived at by inductive reasoning—and what may be called analeptic thought, the recovery of lost events by the same suspension*
>
> —Robert Graves, *The White Goddess,* 1966

## Begetting Conscious Awareness

In the previous chapter I described a "temporal hold" during which thoughts can initiate a "temporary dominant focus" that alters brain activity. The thought process itself is likely to be unconscious. But thinking is not the only way a temporary dominant focus is formed: Thinking addresses the memory store; alternatively, attention addresses the sensory input and intention addresses the motor output during the temporal hold. When we consciously experience "what is it?" we are *paying attention* to a sensory input. When we consciously format "what to do?" we actively *construct an intention* regarding a motor output. Our brain activity is thus shaped by a variety of processes that may or may not be relevant to what we are seeking. William James described the situation beautifully: In order to deal with an issue, we must repeatedly bring our wandering attention (thought and intention) back to focus on the issue we are trying to address. Only when a temporary dominant focus has been formed does observable behavior change, which allows us the opportunity for conscious experiencing. We have all had the experience of "knowing" something and sitting down to write about that something and finding out that what we write has little semblance to what we "know."

## Privacy and Primacy

Today, philosophers of science are concerned with what they call two difficult problems regarding consciousness: the privacy argument that highlights the difficulty in understanding our own and other peoples' consciousness; and the relationship of our conscious experience to brain processes. As a scientist, I find neither of these problems unusually difficult as long as we understand the limitations of what scientific exploration achieves.

The problem of the privacy of our conscious experience is no more difficult to address than the privacy of an atom. Physicists devise tools to ask questions of atoms; psychologists devise tools to ask questions of people and animals. The answers we obtain are, in the first instance, not always clear. Also, such answers may be complementary, as, for example, when a psychologist interviews husband and wife and finds it hard to believe that they inhabit the same household—or when the physicist probes an atom to find a constituent to be both a particle and a wave. In fact, I feel that the answers the psychologist obtains are often more transparent than those that constitute current quantum physics. Also, I continue to be amazed at what the physicist *does* to penetrate the secret life of an atom: he uses ultra-high amounts of energy to smash atoms, and he looks at an oscilloscope for traces, marks, that indicate to him that among thousands of traces the one he is looking for is "actually" there. The task is certainly as daunting as asking someone how *he* feels today or how *he* voted as he emerges from the voting booth. At least the psychologist does not have to smash his subject into little pieces in order to make his inquiry.

In other ways, the privacy argument that someone else's conscious experience is inaccessible is *wrong*. Actually, conscious experience is *unusually* accessible to inquiry: we ordinarily just have to ask someone what he has experienced or is experiencing. We can take the answers at face value, or we can decide to probe further. This does not mean that the issue that has been identified by philosophers should be ignored; just that it has been mislabeled. When one of my children chronically complains of pain, I have a difficult time dealing with his private experiencing of pain; this is not because I don't believe him but because of what I know about the generation of painful experiences. I know from animal experiments performed at Yale and innumerable human surgical procedures that have been performed for the relief of intractable pain (as for instance, pain resulting from a phantom limb) that the longer pain from a bodily injury persists, the more of the spinal cord and brain become involved in maintaining the *duration* of that pain. How does a parent communicate to a child that his pain is really cerebral by now, and no longer originates just in his muscles, as in neuro-myalgia, without being interpreted as saying the pain is "merely psychological?" In such an instance, trying to put forth an interpretation in terms of an efficient causal relation between our brain function and our subjective experience becomes a hindrance.

While teaching medical students at Yale, I shifted the issue of diagnosis and treatment of what we called psychosomatic illnesses, such as stomach ulcers and high blood pressure, from Aristotle's efficient to final causation: Once no obvious current efficient cause for a stomach ulcer has been found, it no longer matters whether the ulcer is diagnosed as having been produced psychologically or biologically. The focus must now be on what can be done. It matters little whether the ulcer was "caused" by psychological stress or by organic excess acidity or both. In fact it is unlikely that these "efficient causes" can even be separated! The medical question that must be answered is: What needs to be *done right now*? Is the ulcer about to perforate? If so, proceed with surgery. If not, will an antacid medication work or can the patient rearrange his lifestyle and receive supportive therapy? Ulcer medicine is "organic;" lifestyle is "psychological." As the discomfort and pain of an ulcer becomes increasingly corticalized, the distinction between matter and mind becomes irrelevant, except in terms of what can be done to alleviate the patient's condition.

The privacy of our experience of pain matters because of what can be done about that pain. The privacy of our perception of red doesn't much matter to anyone, except philosophers. Nonetheless, there is a way to tackle the privacy issue: that is, by giving *primacy* to *our own* experiences as we begin our inquiries into them. I experience the color red. I ask you what the color of a swatch of cloth is and, if you have been raised in the same culture as I was, you will most likely say, "That's red"—unless you happen to be a girl, and you have learned to distinguish red from hot pink or cerise, which is then the color of the cloth for you. If the person you ask is a male who is red-green color-blind, his answer may be "green," and I proceed to test him for color blindness by administering the polka-dot Ishihara test for color blindness to prove that he is indeed color-blind. Furthermore, should the person I ask be located in Somalia, he would probably say that the cloth is black—unless he is a tailor who has traded in imported cloths of many colors. There is no term in the Somalian language for "red," but there are tens of terms for green, which is the color of vegetables upon which the Somalis depend for subsistence.

Two questions immediately present themselves: First, do girls actually *see* color differently from boys? The answer is yes: to some extent, those retinal pigments that absorb the spectrum of radiation that enable us to see are different in males and females. Further, red-green blindness is almost unheard of in girls. The second question is whether we see colors for which we have no experience and for which our society has no language. The obvious answer seems to be "of course," but the obvious answer may not be the correct one. We do know that when it comes to whether we have the ability to make differentiations, thus to be conscious of finer-grain distinctions such as the difference between red and hot pink, the answer turns out to be that it is unlikely.

A personal experience attests to what is involved in making progressive differentiations of finer-grain distinctions. In my case, the differentiation depended on seeing patterns among what initially appeared to be a random distribution of dots. My colleagues at the Yerkes Laboratories in Florida and I were attempting to classify the cellular architecture, the texture, of the nerve cell bodies that make up the thalamus, the halfway house of pathways that extend from our sensory receptors to our cortex. We initially could not see most of the distinctive patterns of cells shown in texts. All we saw at the time looked to us like a bunch of randomly distributed polka dots. After much peering through the microscope and comparing what we saw with texts, we finally, after a year or so, began not only to see what the texts were describing, but also to make innovations of our own which we later proceeded to name and publish. When we persistently attend to our sensory input, we are able to progressively differentiate the composition of the world we navigate; that is, we become more and more conscious of that world and how to navigate it.

## To Summarize

Of course the privacy of our conscious experience is a problem, but it is no different from the problem of the privacy of an atom or molecule. By putting the primacy of our own conscious experience first, we can explore the patterns, the forms that contribute to making up our experience. If that experience involves the experiences of others, *communication* offers us one ready step in breaching the privacy of our own conscious experience and the conscious experience of others. An alternate step is hands-on: measuring and analyzing what we experience. This is the usual path of *scientific exploration*.

## Modes of Awareness

When we begin to examine our awareness scientifically, we find that it comes in at least two “flavors”: our monitoring the world we navigate; and the assessment, the evaluation of the monitoring. For example, you are driving down a highway with a friend. You are having an interesting conversation. The car you are driving maintains its pace on the road (even though not on automatic drive) and stays in its lane. You may even pass an obstructing slow driver. Suddenly you are jarred out of your conversation —out of the corner of your eye you noticed a police car. You intentionally slow a bit, not too noticeably—and in a minute or two resume the discussion: “Ah, where were we?” As the driver of the car, you must have been “aware” all along of the road in front of you (and behind you) and how to navigate it. At the same time you were engrossed “consciously” in the conversation.

Since the 1960s, I have called attention to the difference between the surface and the deep structure of brain activity. The surface structure is composed of brain circuits that can rapidly lead to the execution of automatic behavioral actions. When something out of the ordinary occurs, it activates the deep structure of fine fibers in our brains. Thus, the more automatic the processing, the *less* of that fine-fibered web of our brain becomes engaged. Circuits are used when we activate our well-established habitual input-output, sensory-motor reactions. Only when an event occurs in a non-routine, relatively unusual, or “novel” circumstance, calling for directed attention and the evaluation of the situation—a circumstance such as spotting the police car—does deep processing become involved.

Initially I had thought that monitoring per se necessitated the involvement of the frontal and related systems. I had expected, therefore, that these systems of the brain would be critical, in some fashion, to enhance deep processing. And, to some extent, this is correct: When we are delaying, while making a *complex* choice, cells in the systems of the back of our brain reflect that delay. When the prefrontal cortex of an animal is anesthetized, these cells are no longer active during the delay period, and the animal fails to execute the correct choice.

## Blind-Sight

My focus on the frontal cortex was disrupted when Lawrence Weiskrantz, retired head of the Department of Experimental Psychology at Oxford, performed experiments on patients with occipital lobe damage. These patients were able to navigate their world but were unable to “see” what they were navigating. Weiskrantz named this condition “blind-sight.” I had thought that our frontal lobes were the critical parts of the brain that made human awareness possible; here we have patients who lose their awareness with injuries to the opposite end of the brain! But on rethinking the problem I came to see that the frontal systems are invoked when assessment and evaluation of a situation demands directed attention, and that blind-sight dealt with monitoring the navigation of our world, not evaluating it.

Blind-sight patients do not see half of the world that is in front of them. The half that is blind is on the side opposite the side where their brain injury is located: for instance, if the injury is on the right side, they are blind to the left side of what lies before them. When shown an object such as a box or a ball, they cannot see the object. But when asked to *guess* whether there is an object in front of them and whether the object is a box or a ball, they guess correctly on about 80% to 90% of the trials. When this and similar tasks are repeated, and the patients are asked how they managed to guess so well, they are unable to give an answer.

A patient's ability to navigate his world unconsciously after a brain injury is not limited to vision. A more common form occurs after injury to the right parietal lobe: later in the chapter we will encounter a patient who no longer felt that her limb was a part of her body, but her limb worked well while bringing a cup of coffee to her mouth (often to her surprise).

Another group of patients are "mind-blind" in that they cannot consciously "read" the nonverbal gestures of others, but may nonetheless communicate well verbally. We have already discussed a patient who had the opposite disability: she could no longer "read" her own body language; she stuffed herself but felt no hunger.

All of these instances fit the general concept that we use at least two types of conscious processes in navigating our world. One type *monitors* our navigating, the other *assesses* the monitoring and directs our attention to where it is needed.

## The Objective Me

A patient's inability to be consciously aware of *how* he navigates in the presence of reasonable navigational skills comes in several categories: One, of which blind-sight and the lack of body awareness are examples, is produced by injuries of the posterior parts of the brain. The second kind of disability follows from injuries to the fronto-limbic parts of the brain.

These injuries can result in loss of feelings of hunger and thirst as well as of familiarization. But I'll begin with the story of a most articulate student in one of my classes who had had a stroke in the right parietal lobe of the posterior part of her brain.

Mrs. C. provided an excellent example of an inability to call her own arm into consciousness. She was seated to my right during a weekly seminar, and I noted that occasionally her left arm and hand would move in a strange fashion. While pointing to her left arm, I asked Mrs. C., if she was all right. She replied, *"Oh, that's just Alice; she doesn't live here anymore."* Mrs C. wrote her subsequent term paper describing her experience. Here are some excerpts from this most informative paper:

> *I was doing laundry about mid-morning when I had a migraine. I felt a sharp pain in my left temple and my left arm felt funny. I finished my laundry towards mid-afternoon and called my neurologist. He told me to go to the emergency room. I packed a few things and drove about 85 miles to the hospital where he is on staff (the nearest was 15 minutes away). In the E. R. the same thing happened again. And again, the next morning after I was hospitalized, only it was worse. The diagnosis of a stroke came as a complete surprise to me because I felt fine, and I didn't notice anything different about myself. I remember having no emotional response to the news. I felt annoyed and more concerned about getting home, because I was in the process of moving.*
>
> *Not until several days later while I was in rehabilitation did I notice strange things happening to me. I was not frightened, angry or annoyed. I didn't feel anything– nothing at all. Fourteen days after I was admitted to the hospital, I became extremely dizzy, and I felt I was falling out of my wheelchair. The floor was tilting to my left and the wheelchair was sliding off the floor. Any stimulus on my left side or repetitive movement with my left arm caused a disturbance in my relationship with my environment. For instance, the room would tilt down to the left, and I felt my wheelchair sliding downhill off the floor, and I was falling out of my chair. I would become disoriented, could hardly speak, and my whole being seemed to enter a new dimension.*

*When my left side was placed next to a wall or away from any stimuli, this disturbance would gradually disappear. During this period, the left hand would contract, and the arm would draw up next to my body. It didn't feel or look like it belonged to me. Harrison (my physician) moved the left arm repeatedly with the same movement, and a similar behavior occurred, except I started crying. He asked me what was I feeling, and I said anger. In another test he started giving me a hard time until the same episode began to occur, and I began to cry. He asked me what I was feeling, and I said anger. Actually I didn't feel the anger inside but in my head when I began to cry. Not until I went back to school did I become aware of having no internal physical feelings.*

*I call that arm Alice—Alice doesn't live here anymore—the arm I don't like. It doesn't look like my arm and doesn't feel like my arm. I think it's ugly, and I wish it would go away. Whenever things go wrong, I'll slap it and say, "Bad Alice" or "It's Alice's fault." I never know what it's doing or where it is in space unless I am looking at it. I can use it, but I never do consciously because I'm unaware of having a left arm. I don't neglect my left side, just Alice. Whatever it does, it does on its own, and most of the time, I don't know it's doing it. I'll be doing homework and then I'll take a sip of coffee. The cup will be empty. I was drinking coffee using that hand and didn't know it. Yet I take classical guitar lessons. I don't feel the strings or frets. I don't know where my fingers are nor what they are doing, but still I play.*

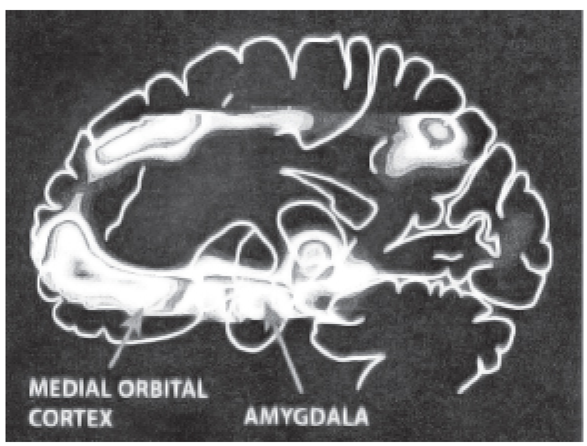
*How do I live with an illness I'm not aware of having? How do I function when I'm not aware that I have deficits? How do I stay safe when I'm not aware of being in danger?*

My student's *egocentric* integrity had become disrupted: the form of her tactile and kinesthetic space-time had changed radically, as evidenced by her feelings of tilting and falling. Patients who are blind-sighted suffer from a disruption of their *allocentric,* that is, other-centered— visual and auditory—organization. Egocentric and allocentric integrity form a patient’s mode of conscious awareness within which he regards both the self and the other as objects.

## The Narrative I

The above situation in which Mrs. C’s arm had become an alien Alice contrasts sharply with the following observations made by Chuck Ahern, whose PhD thesis I supervised. Ahern based his study on observations made on an eight-year-old boy while he taught him how to read:

TJ had an agenesis [lack of development] of the corpus callosum [the large nerve fibers that connect the hemispheres of the brain] with a midline cyst at birth. During the first six months of his life, two surgical procedures were carried out to drain the cyst. Recently performed Magnetic Resonance Imaging (MRI) showed considerable enlargement of the frontal horns of the lateral ventricle— somewhat more pronounced on the right. The orbital part of the frontal lobes appeared shrunken as did the medial surface of the temporal pole.




*93. fMRI of Limbic Cortex Lesion*

*TJ lost the ability to process episodes of experience. When TJ returned from a trip to the Bahamas he did recall that he had been on the trip; however, the details he could recount about the trip numbered fewer than five. His estimates of how long it had been since his trip were typical in that they were inaccurate and wildly inconsistent on repeated trials. Also, the first five times back at tutoring he stated that he had not been at tutoring since his trip. It appears that he is unable to place in sequence those* *few past events that he can recall. Nonetheless, he can answer questions correctly based on his application of general knowledge about development, e.g., he knows he was a baby before he could talk because "everyone starts as a baby." But, one day he asked his tutor if he knew him when he was a kid, indicating, I think, his incomprehension of the duration of each of these developmental periods and his unawareness of what events constituted such a period for him.*

*Furthermore, TJ appears to have no ability for quantifying the passage of the duration of an experience [what Henri Bergson (1922–1965) called* durée*] and no experiential appreciation of the meaning of units of the duration of an episode. For example, a few minutes after tutoring begins, he cannot say—even remotely— how long it has been since the session started. He is as apt to answer this question in years as in minutes. He does always use one of seven terms of time quantification (seconds, minutes, hours, days, weeks, months or years) when asked to estimate the duration of an episode but uses them randomly. He can put these terms in order, but does not have any sense of their meaning or their numerical relationships to one another.*

*TJ is aware that he has a past, that events have happened to him but he cannot recollect those events. He also spontaneously speaks of events in his future such as driving an automobile and dating and growing a beard. He has play-acted on separate occasions his own old age and death. TJ is capable of excitement about the immediate future. On the very day that he was going to the Bahamas he was very excited as he exclaimed repeatedly: "I'm going to the Bahamas." But when his tutor asked him when, he said blankly: "I don't know." He also displayed keen anticipation when one day he saw a helicopter preparing to take off from the hospital. The helicopter engines revved approximately 13 minutes before it took off and TJ become increasingly more vocal and motorically active, laughing as he repeated "When's it going to take off?" He also anticipates future punishment when he is "bad." He is aware, on some level,* *of the immediate future in his constant question "what's next" which he asks his mother at the end of each activity.*

*There are a variety of other occasions on which he demonstrated this capacity regarding tempo (as opposed to evaluating the duration of an experience.) There have been several breaks in his usual thrice-weekly tutoring schedule. Each of four times this schedule has been interrupted, he has run to meet his tutor when he approached rather than waiting inside as he usually does. Also, on these occasions he has typically asked if his tutor missed him. However he states he does not know how long it has been since his last session, and there was no evidence that he knew it had been longer than usual.*

*TJ compares who walks faster or who draws faster. He has at least a basic sense of sequencing as when he says "I'll take a turn and then you take a turn." He also uses terms like "soon" and "quick" correctly in conversation. For example, when he wanted to do a drawing at the beginning of a session, and his tutor said that we needed to begin to work, he countered "this will be quick." Unsurprisingly, he finished his drawing at his normal pace. He somehow seems to use such terms correctly without any experiential appreciation of them. (From Chuck Ahern)*

These two case histories illuminate two very important dimensions of self. One dimension, portrayed by Mrs. C., *locates* our body's configural integrity as an objective "me" in the space-time world we navigate. The other dimension, highlighted by TJ, *narrates* meaningful episodes of circumscribed duration of our experience. Without such narrating, the events comprising the experience fail to become relevant and evaluated with respect to an autobiographical self, a narrative "I."

The locational dimension includes clock-time, what the Greeks called *chronos*. *Chronos* is the "time" Minkowski and Einstein related to space. Location for a moving organism is always in space-time.

Narrating entails not only our experience of duration but also Robert Graves's "proleptic thought," the decisive moment; what the Greeks called *kairos*.

We exist in two very different worlds: a space-time world we navigate, and a narrative world we inhabit.

(An excellent review of the history of differentiating the objective "me" from the hermeneutic "I" can be found in Hermans, Kempen and van Loon's article called "The Dialogical Self: Beyond Individualism and Rationalism." *American Psychologist,* 1992.)

## The Importance of TJ

TJ was of additional interest to me for two reasons: First, despite having sustained his brain impairment before birth, he could learn to read and to communicate. Therefore, organization of our "Objective Me" does not depend on our ability to process the episodes that constitute our narrative self.

Second, TJ is also of special interest because, in spite of devastating damage to his medial frontal and temporal lobes which left him with very little of what we often call the "limbic" system, essentially he has remained emotionally and motivationally intact. He can express "worries" and "interests"; his appetites are normal as are his satiety processes. Hence, Harvard's Walter Cannon's theory, based on his experimental results obtained in the 1920s and 1930s, is most likely correct: the thalamus and hypothalamus (and even the brain stem) are more essential to the intensive dimension of emotional experience and expression than are the limbic parts of our forebrain. The limbic amygdala and the non-limbic upper basal ganglia, as well as the hippocampal system, modulate thalamic, hypothalamic and brain stem processes. In turn, the pre-frontal cortex makes it possible to formulate more precisely these narrative aspects of our conscious experience.

## The Other

The "Narrative I" has a companion in a "Caring Other." Brain-imaging techniques and microelectrode recordings of the responses of single brain cells, have shown that the front parts of the right hemisphere of the human brain become activated not only when we accomplish an action, but also when we watch someone *else* accomplish that action. This finding has been interpreted to indicate that *a brain process is involved in imitating the actions of others*.

Another part of our frontal cortex becomes activated not only when we experience discomfort, but when we watch someone suffer. *Empathy with another involves an identifiable brain process when we consciously experience it.*

On the basis of my research and that of others, I established for myself the difference between an "Objective Me" and a "Narrative I." But given the finding that our brains are involved when we watch another perform a task and when we emotionally empathize with another's pleasure or pain, this view of two possible "selves" is not enough. The "Narrative I" depends on stringing episodes together into a story. Otto Rossler, a pioneer in the creation of the discipline of non-linear dynamics, has more generally referred to the process of storytelling as *pathway optimization*. We tell stories and we use language to tell them. Language, pathway optimization, is a *left* hemisphere function in most cultures. But our *right* hemisphere *aggregates* episodes, *weaving them together* in a more subtle fashion. Thus, caring, interest, joy and sorrow, and other intensive dimensions of our experience become conscious.

Just as the "Narrative I" is processed mainly by one hemisphere—the front part of the *left hemisphere*—so also does the "Objective Me"—as exemplified by the brain-injured, "blind-sighted" and "Alice doesn't live here any more"—involve mainly one hemisphere, the back part of the *right hemisphere*. What does the corresponding part, the back of the *left hemisphere* of the brain do? It enables the semantic, dictionary aspects of language and the concepts upon which languages are based. Concepts, when shorn of their complexity, finally boil down to our "pointing at" what is being spoken about. Rossler has called this aspect of the dynamics of a complex process such as language a "directional optimizer." This is the allocentric, or other-centered, aspect of our conscious processing, the semantic "Other" that complements the egocentric "Me."

Paradoxically, we experience the "Narrative I" in a mode that philosophers would refer to as a third-person mode: for example, in remembering that when I was a six-year-old boy I had set up a weather station at my school in Switzerland, I tell a story about "that boy" even though it is "I" myself who happens to be the boy. By contrast, "Imitation" and the "Caring Other" are experienced in the first person: I personally am imitating others and share their joy or suffering.

Just as, paradoxically, we experience the egocentric "Objective Me" in the first-person mode. After Mrs C. had suffered her brain injury, "Alice didn't live here any more." But before the injury, Mrs. C's arm did live with her. In another example, it is intimately "my" arm that itches from a mosquito bite. Furthermore, our allocentric "seeing" is also experienced in the first-person mode; the blind-sighted person has lost a part of his ability to subjectively experience, to "see" the world he navigates.

## To Summarize

Left hemisphere language-based processes—the Narrative I and the Semantic Other—*become experienced* in a third-person mode. Right hemisphere processes—Imitating, Caring and, paradoxically, the Objective Me and its Navigable World—*become experienced* in a first-person mode. It is our brain cortex that allows our consciousness to become so rich.

## Unconscious Processing

A great deal of our behavior is habitual, automatic and unconscious. In normal individuals, with no brain damage, switching from unconscious to conscious behavior occurs readily when a situation changes suddenly and unexpectedly. At other times, when circumstances change more gradually, we have to exert considerable effort in "tacking," as a sailor would put it, to take advantage of changes in the direction of the wind. What might be the difference in *how* the brain operates during these two modes of changing?

Freud considered modes of unconscious and conscious operation in terms of several "levels:" conscious, preconscious and unconscious, suggesting that there is a "horizontal" barrier between our conscious, preconscious and unconscious layers of processing. Freud further proposed that "repression" operates to push our memories into deeper layers where they can no longer access awareness. In the *Project*, Freud treats memories as memory-motive structures—what today we would call neural "programs"—located in the basal ganglia, proposing that our awareness is enabled through the connections of these programs with the cortex. In Freud's view, the connections to and from our cortex determine (via attentional processes) whether a memory-motivated wish comes to our consciousness and thus becomes available to us for reality testing.

## The Hidden Navigator

My interpretation of the relationship between conscious and unconscious processing is different from Freud's and was initiated by observations made on hypnotized subjects. On the basis of experimental observations made on hypnotized subjects at Stanford, Jack Hilgard described what he called "a hidden observer." A hidden observer participates even when the subject is unaware of what is motivating his own behavior. It is as if the hypnotized subject knows, in some way, that what is guiding his behavior is different from his ordinary experience. In my laboratory, Helen Crawford, professor at the Virginia Technical University, and I showed that those subjects who demonstrated the hidden observer phenomenon were those in whom we could not induce an experience totally away from the experimental setting. However, if the subject could immerse himself or herself in being on a beach in the Caribbean with his or her girl- or boyfriend, no hidden observer accompanied them.

These observations have led me to suggest a modification of the picture that Freud presented of "levels" where "unconscious wishes" are suppressed and repressed. My view is inspired not only by the observation of a hidden observer, but also by my post–World War II approach to analyzing brain function: from inside out: An alternative model of the relationship between conscious and unconscious processes, I suggest, is that of language. A skilled multi-linguist "knows" several languages—but uses only one in a particular context, a particular situation. He may find the language inadequate to his purpose and knows that he could express himself better in another, momentarily hidden tongue, but how to accomplish this in the current context seems very difficult. As my colleague Georg von Békésy once remarked to me, German is so much better in expressing nuances— how frustrating it is to write papers in English!

Sometimes, when we are in the presence of others who can also speak several languages, our ability to switch between them comes easily. At other times, a language, which may have been useful to us at an earlier age, has been "suppressed." For instance, my mother's native language was Dutch, but she learned English, French and German as a young child. In Chicago, as I was growing up, she spoke an almost flawless English when we were out shopping or when she was entertaining guests. At these times there was no groping for a Dutch phrase or other hesitancy that would accompany an effort at translation from one language to another. She was consciously using English, and her other languages had become "repressed" into unconsciousness. But within our family, in a more familiar context, she spoke in whatever language best fitted what she wanted to express, sometimes multilingually in a single sentence.

We learn to process our navigable world, and to communicate, at a particular age and in a particular "language." This language may become inappropriate at another period of our life, but we may still use it, albeit inappropriately, in certain circumstances much as when a person with Tourette's syndrome makes embarrassing statements during "tics" due to damage to his middle basal ganglion (the globus pallidus.) Psychotherapy for ordinary patients can help point out when their "hidden *navigator*" is impeding a current communication.

As I learned from Piaget, the paths of our cognitive and emotional/motivational development do have similarities. Language offers a powerful model for understanding the difference between our current conscious awareness of how we feel and the patterns of experiencing and behaving that are no longer used, or useful, but become inappropriately activated in "familiar" situations. One form of psychotherapy is to access these "hidden" patterns by attempting to re-establish the familiar interpersonal context, *en famille,* that existed when the earlier "language" modes were used, and to bring them into consciousness in a more current context. This mode of therapy is called "transference;" most often the therapist temporarily becomes the patient's parent "figure."

## How Unconscious Is Unconscious?

The Argentine philosopher Matte Blanco, in his 1975 book *The Unconscious as Infinite Sets*, proposed that we should define consciousness as our ability to make clear distinctions, to identify (that is, to categorize) alternatives. Making clear distinctions would include being able to tell personal egocentric from extra-personal allocentric experience; to distinguish one episode from another in a narrative or an imitation from a self-generated action; or an empathic from a self-pitying response to a situation.

By contrast, unconscious processes would, according to Blanco, be composed of infinite sets "where paradox reigns and opposites merge into sameness." When infinities are being computed, the ordinary rules of logic do not hold. As Lewis Carroll was fond of pointing out, dividing a line of infinite length results in two lines of infinite length: paradoxically, one = two. When we are deeply involved with another human being, our capacity for love and ecstasy is evoked but, paradoxically, so also is our capacity for suffering and anger to occur.

My interpretation of the conscious-unconscious distinction agrees with Matte Blanco's. To bring our well-springs of unconscious behavior and experience into consciousness means making distinctions, categorizing and becoming informed—in the sense of reducing uncertainty, the number of possible alternatives in making choices.

Within the scientific community, clarity regarding the details of how such distinctions are achieved did not gel until the late 1960s, when several theorists began to point out the difference between feedback, or homeostatic processes, on the one hand, and programs—which are feedfor-ward, homeorhetic processes—on the other.

Feedback mechanisms, though they are dependent upon error processing, may eventually become ultra-stable. By contrast, feedforward processes are hierarchical "complex" organizations that can readily be reprogrammed by changing the way they are chunked. The difference between feedback and feedforward processing turned out to be the same as the distinction that had been made by Freud between primary (automatic) and secondary (voluntary, reality testing) processes.

When these interpretations are considered seriously, an important change in views becomes necessary: our unconscious processes, as defined by Matte Blanco, are not completely "submerged" and unavailable to our conscious experience. Rather, our unconscious processes produce feelings which are difficult for us to localize in time or in space and difficult for us to identify correctly. Indeed, our unconscious processes serve to construct those emotional dispositions and motivational contexts within which we are then able to construct our extra-personal and personal realities. Our feelings are to a large extent undifferentiated, and we tend to cognize and label them within a context: that is, according to the circumstances in which those feelings become manifested.

It is in this undifferentiated sense that our behavior is unconsciously motivated. When I burst out in anger, I am certainly aware that I have done so and of the effects of my anger upon others. I may or may not have attended the build-up of feeling prior to the blow-up. I may have projected that build-up onto others or introjected it from them. I might even have been made aware that all these subliminal processes can occur through the guidance of a friend or a therapist, and still have found myself intensely upset. Only when we can clearly separate the events leading to the upset into alternative or harmoniously related distinctions such as anger, fear, hate, or a similar bevy of positive feelings, is unconscious control converted into conscious control.

During the 1930s, Willhelm Reich devised a technique called "process psychotherapy" by which complex unconscious processes are brought to consciousness: Reich started by pointing out some of a person's nonverbal behaviors such as facial expressions and gestures which the patient uses routinely and unconsciously. Additionally, Reich called attention to the effect those facial expressions and gestures have on others. Gradually the therapy proceeds to verbal language and strips the subject of other aspects of what Reich called the person's "character armor." The process of stripping is a process of clearly differentiating one expression or gesture from another—and the effect that such an expression can have on the experience and behavior of others in one or more clearly differentiated situations. Once these distinctions are noticed, conscious experience has supplanted unconscious processing and, as a result, the interpersonal world the person navigates changes dramatically.

As an example, some years ago, I realized that I rarely made eye contact during a conversation. I was paying attention to the other person's lips, lip-reading in order to enhance my understanding of what the person was saying. Since then, I have made a conscious effort to make eye contact during conversation. As a result, people have commented on my attentive listening and what an interesting conversationalist I am. This despite the fact that I now understand considerably less of what the other person is saying! My nonverbal behavior signals to them that they are being attended, where before, my nonverbal behavior signaled that I was engrossed in my own process of deciphering a conversation.

## In Summary

"Unconscious" processes are actually more diffi-cult to describe than conscious processes. However, Matte Blanco's definition is a good one: consciousness depends on the ability to differentiate; the undifferentiated compose unconscious processes. This definition fits my proposal that unconscious processes are like currently unused language systems of persons who are fluent in several languages. The unused languages are "stored" in their ultra-deep processing form until activated. But such hidden languages can still exert an influence on current behavior, such as the complexity of articulation, or the relevance of the behavior to the current social context. Psychotherapy addresses maladaptive processing by bringing to current consciousness these hidden, unconscious language-like processes.

# Chapter 24
## Mind and Matter

This chapter is what the rest of the book is all about.

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*The book of nature is written in the language of mathematics.*

—Galileo Galilei, 1623

*Mathematics brings together phenomena the most diverse, and discovers the hidden analogies which unite them . . . it follows the same course in the study of all phenomena; it interprets them by the same language, as if to attest the unity and simplicity of the plan of the universe, and to make still more evident that unchangeable order which presides over all natural causes.*

—Jean Baptiste Joseph Fourier

*The Fourier theorem is probably the most fundamental in physics.*

—Richard Feynman, *The Feynman Lectures on Physics*, 1963

The formulations of Gabor and Fourier provided the formal tools I needed to comprehend not only the theoretical concepts described in previous chapters, but also the experimental results we were producing in my laboratory. My aim from the outset of my research had always been to explore the relationship of our brain to psychology—that is, to our perception, our behavior, our thoughts, motivations and emotions. Initially, my aim had been to eliminate "mentalism"—the idea of a mystical mental principle— from psychology just as biologists of the 19th century had eliminated "vitalism"—the idea of a mystical vital principle —from biology. This aim subsequently led me into a series of unexpected adventures that proved to be a true odyssey. In the 1950s, I was temporarily sustained by the storm of behaviorism—a storm that provided me the skills to steer a clear course between the Scylla of mentalism and the Charybdis of materialism.

My "growing up" from behaviorism—as Lashley had ironically put it —began in earnest when, in testing patients in clinical situations, I found that a patient's *behavior frequently did not reflect what he told me he was feeling*. Thus it was necessary for me to take note of the patient's "inner life" in order to obtain a full profile of his psychological life. This limitation of the behaviorist approach to psychology should not have come as a surprise: after all, every day, we see all around us people (politicians?) who say one thing and do another. But, in my work with monkeys, I had been concentrating on nonverbal behavior, to the exclusion of what verbal behavior has to tell us.

## From Behaviorism to Phenomenology

I reported my observations of the discrepancy between a patient's behavior and her verbal expressions in Sigmund Koch's multivolume *Psychology: A Study of a Science* (1962). I described how we could begin to relate verbal and nonverbal behaviors and what this relationship might signify for our future study of the brain. I began to explore the consequences of what I had learned from this disparity in such venues as my 1973 paper, "Operant Behaviorism: Fad, Fact-ory and Fantasy?" I made my final step to "adulthood" in my 1979 paper "Behaviorism, phenomenology and holism in psychology." In this paper I observed that now that we had achieved a *science of behavior*—we needed to develop a *science of psychology*. I suggested that such a science of psychology *begin* our scientific explorations with the *phenomena* (including behaviors) we observe and experience. I also noted that phenomenology lacked formal structure and that we needed to provide that structure with experimental results that would of necessity include studies ranging from those on the brain to those of society. Skinner, who rarely asked anyone for a copy of a paper, asked me for one. I was pleased.

In a series of papers, as well as in the final chapters of my 1971 *Languages of the Brain: Experimental Paradoxes and Principles in Neuropsychology*, I formulated such a structure for a phenomenological psychology on the basis of the experiments reviewed in that book. My formulation began, though did not end, with what is called the "dual aspect:" that is, a dual view of the relationship between brain and mind: that is, we have *mind talk* and we have *brain talk*. But I noted that the "talk" has to be *about* some common something—and what this something might be was not addressed in the dual aspect approach to the mind-brain relationship. I also had no answer for what this "something" might be, but I did propose a crucial change: for "talk" *I substituted structure; that is, form as "pattern.*" We have patterns that compose psychological processes and patterns that compose brain processes. This shift meant a shift to a view in which patterns were *embodied* in a variety of ways that included language and culture.

I used music as an example. As I've noted in earlier chapters, music can be expressed in a score on a sheet of paper, in a performance, or on the roller of a player piano —the great granddaddy of the audiotape. And, as I also noted, we are in a position to determine the transformations that form the relationship among patterns, say between a visual score, a visual process in the brain, a motor performance, an instrument's "output" patterns, and those of the auditory sensory and brain process.

Unfortunately, the importance of this distinction between "view" and "embodiment" has not as yet penetrated the philosophical establishment. Thus Harald Atmanspacher, the editor-in-chief of the journal *Mind and Matter,* introduces the 2007 issue on "Many Faces of Dual Aspects" with an excellently phrased summary of current views: "Dual-aspect approaches (or double-aspect approaches) consider mental and material domains of reality as aspects, or manifestations, of one underlying, unseparated reality."

Atmanspacher, a good friend, fails to emphasize or address the difference between “aspects” and “manifestations,” though he discusses the importance epistemic and ontic issues. In my presidential address to the society of Theoretical and Philosophical Psychology, published in 1986 as “The Cognitive Revolution and Mind-Brain Issues” in *The American Psychologist*, I had gone a step further in beginning to identify that ontic reality as “energy.” This was a step in the right direction, but it would take another fifteen years before I would be able to spell out the details of that commonality.

The detail of my proposal rests on Gabor wavelets (or similar “quanta of information”) that characterize both 1) *communication, a mental process,* and 2) *processing in the receptive fields in the sensory cortex of our material brains.* The Gabor functions (constrained Fourier transforms) thus implement *both communication and brain processes*.

## Descartes

The story that emerges from my studies is consonant to a considerable extent with what Descartes had actually proposed, not what most current philosophers and scientists are interpreting him to have said. My espousal of Descartes’s proposal is *contrary* to the current views of most brain scientists and many philosophers of science: *Thought can be defined technically in terms of Shannon’s measure of information; brain is made of the matter that physicists have been studying for centuries*.

Philosophers and brain scientists have focused on Descartes’s distinction between mind and matter and have, in many instances, come to feel that the distinction is, in the words of John Searle, “the worst catastrophe” ever to hit science and philosophy. (Searle suggests that “mind” is a secretion of the brain much as bile is a secretion of the liver. Searle limits his analysis to efficient causation—and I have covered the restrictions of efficient causality for the mind/ brain issue throughout this book. Furthermore, liver and bile are both material, whereas brain and mind are different in kind.)

Descartes was fully aware of the arguments that Searle now uses. Descartes’s views are illustrated in his correspondence with Princess Elisabeth of Bohemia where he addresses the issue of the *union* of mind and body. In a passage that comes as a reply to the Princess, Descartes writes: *"But it is by means of ordinary life and conversation and in abstaining from meditation and from studying things that exercise the imagination, that one learns to conceive the union of soul and body.*" (*The Essential Descartes*, 1969, emphasis mine)

The Princess's arguments for a unitary approach to mind and body, including specifically the operations of the brain, are so lucid and up-to-date that John Searle could well have written them. In fact, the October/November 2006 issue of the *Journal of Consciousness Studies* is devoted to Galen Strawson's current interpretations of Descartes and his correspondence with Princess Elisabeth that are in many respects similar, but in some other respects rather different from the view that I had developed and am describing here: Strawson heroically wraps Descartes's proposal in current philosophical physicalist and pan-psychic garments. I have instead chosen to look to science for a deeper understanding.

By contrast to the focus by philosophers on Descartes's analytic distinctions, mathematicians have been sustained by Descartes's innovative insights into *coordination*: Cartesian coordinates. *The two sides of Descartes's thinking are not in conflict: distinctions lead us to conscious awareness; coordination leads us to meaningful valuation of those distinctions*. *What is really new in the results of our research performed over the last half-century is that we have found that, to some extent, distinctions between thought and matter are processed by the posterior regions of the brain while union between thought and matter is forged by fronto-limbic systems*. Descartes had an intuition that attitudes in the form of emotions and motivations played a special role different from thinking. In the following quotation note that, for Descartes, passions help to fortify, preserve and conserve thoughts (in today's thinking, by way of reconsolidations of memory).

> *The utility of all passions consists alone in their fortifying and perpetuating thoughts which it is good to preserve, and which without that might easily be effaced . . . And again, all the harm which they can cause consists in the fact that they fortify and conserve others on which it is not good to dwell. (*René Descartes, *Treatise on the Passions of the Soul*, 1649*)*

I am especially intrigued by Descartes's indication that the passions (feelings) fortify thoughts. In a sense, as proposed by Stevan Harnad, the founding editor of the *Journal of Behavioral and Brain Sciences*, this accounts for the perennially unexplained aspect of our sensations that we call "qualia," the "feeling" of a color or sound or taste. Also, intriguing is the idea that "feelings" help to establish and preserve thoughts, an idea encapsulated by Olga Vinogradova, a student of Eugene Sokolov: *"To establish a memory, an ounce of emotion is worth a pound of repetition.*"

My opinion is that, taken as a whole, Descartes's insights are supported by the scientific evidence (especially that pertaining to processing by the frontolimbic forebrain) that has accumulated over the past two centuries. From the viewpoint of understanding the "particular go" of the relationship between brain and psychological processing, Descartes's contributions provide a most *helpful* beginning.

## Fourier

My story of the development of a solid scientific basis for developing Descartes's proposal regarding the mind/brain relationship begins with Joseph Fourier. I have already discussed Fourier and some of the uses to which his mathematical formulations have been put during the past two centuries. Fourier lived at the turn of the 18th to the 19th century. French mathematics was, at the time, the best in Europe, but the Arabs had a longer tradition of excellence, which Napoleon wanted the French Academy to mine, so he put Fourier in charge of the scientific aspects of the Egyptian military expedition. Fourier returned to France from Egypt after two years and presented to the Academy what we now call the Fourier theorem. Fourier had developed a method for making a transformation from the space-time domain within which we navigate, into the spectral domain for the purpose of measuring heat—and vice-versa. Transforming into the spectral domain is the very technique that Gabor employed to develop his holographic process. In Fourier's hands, his method allowed him to measure the spectral properties of radiant energy such as heat and light. Fourier was immediately elected to the French Academy on the basis of his invention.

As noted in Chapter 5, within a month, Laplace, the senior mathematician at the time, showed that Fourier failed to provide a tight mathematical proof of his theorem. Laplace was not successful in ousting Fourier from the Academy, but he did manage to prevent Fourier from publishing in any major mathematical journal for a decade. Fourier published his work in privately owned journals, and toward the end of this decade-long siege, received a major award because of the usefulness both to mathematicians and physicists of his contribution. Laplace finally began to see the merit of Fourier's approach and the two eventually became friends.

Of course, Laplace was right. Even today, there is argument as to whether there is a really tight mathematical "proof" of Fourier's theorem. Nevertheless, his procedure *works*. And it works in a very fundamental way, as the Richard Feynman quotation at the beginning of this chapter indicates. Mathematics is about ideas. The proofs necessary to test these ideas may come along much later, once new methods of thinking have been developed.

Once, while I was attending one of David Bohm's classes, he wrote a set of some six equations on the blackboard to make a point. I don't recall the equations he wrote or even what his point was, but I do remember Basil Hiley, Bohm's mathematician-collaborator over the previous decades, nudging me with his elbow: with a few swear words he muttered, "Great idea but it'll take me ten years to provide a proof with additional equations to fill the gaps between his."

## Waves and Their Interference Patterns

What then was Fourier's great idea? As developed in Chapter 2, "heat," as well as "light," has ordinarily been thought of as coming in waves or particles. Fourier provided us with a way to sample a wave: He shifted the wave onto itself so that the peak of the shifted wave was superimposed somewhere other than at the peak of the initial wave. This produced crossings of the waves. A number could now be assigned to the amplitude (the vertical distance from the halfway point of the wave) of the crossings. The shift had produced an interference pattern consisting of reinforcements and cancellations where the wave intersects with itself. The interference pattern constitutes a spectrum. Calculations of interactions among spectra could now be made by way of their coefficients.

Fourier knew that a problem still remained: Just how far should the wave be shifted onto itself? Fourier's answer was half a wavelength or 90 degrees. Waves are often designated as sine waves and cosine waves. Being a non-mathematician, it took me years to try to understand how waves could be designated in terms of their sines and cosines. Finally it dawned on me: waves can be represented as a continuous progression over space, or, as on an analogue clock face, a circular motion over time. (The clock represents the diurnal wave, the cycle of day and night.) When considered as a circle, any point on the wave can be triangulated and thus its sine and cosine stipulated. I was proud of myself for figuring this out. I was even happier when I read Fourier's original manuscripts that showed how he had labored before coming to this insight in much the way that I had. (Neither of us had thought about the Pythagoreans!)

## The Fourier Diagram

Fourier's theorem allows us to transform between spectra and the space-time dimensions of the world we navigate. This was to have many far-reaching practical applications, such as in analyzing EEGs; in image processing, as in PET scans and fMRI; as well as in statistics, where the Fast Fourier Transform (FFT) is used to correlate various data sets.

Even more intriguing are some of the insights quantum physicists have derived from their application of the Fourier Theorem. I have recently extended their insights to come to an understanding of the brain/mind issue.

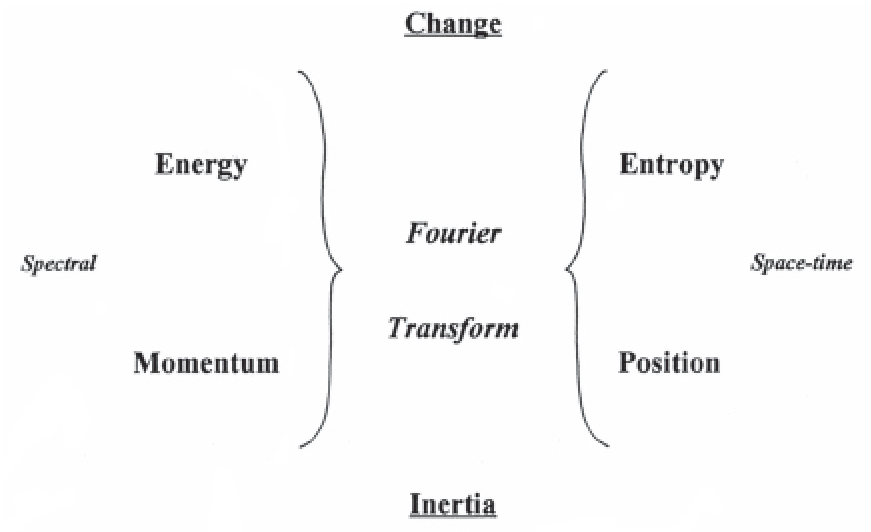
The Fourier diagram provides my summary of these insights. The diagram is based on a presentation at Berkeley made during the early 1980s by the Berkeley physicist Jeff Chew at a conference sponsored by a Buddhist enclave. I had known about the Fourier transformation in terms of its role in the analysis of brain electrical activity and in holography, but I had never appreciated the Fourier-based fundamental conceptualizations spawned by concepts in quantum physics, as portrayed in the diagram. I asked Chew where I might learn more about these relationships, and he noted that he'd gotten them from his colleague Henry Stapp, who in turn had obtained his view from Jacques Dirac. As early as 1929, in a paper about "The Quantum of Action and the Description of Nature," Niels Bohr had noted that "the analysis of our sense impressions discloses a remarkable independence of . . . the concepts of space and time on the one hand, and the conceptions of energy and momentum . . . on the other.”

I had had monthly meetings with Chew and Stapp for almost a decade, and I am indebted to them, to David Bohm and Basil Hiley, and to Eloise Carlton, a mathematician working with me, for guiding me through the labyrinth of quantum mathematical thinking. As I am not a mathematician, I had to get over the aversion many of us have to trying to decipher formulas and equations. I found that in mathematics there is usually an abbreviated explanation of the ciphers used in the text preceding and following the equation. This worked well for me when physicist Kunio Yasue and anesthesiologist Mari Jibu wrote the mathematical appendices for my 1991 book, *Brain and Perception*.

The diagram summarizes a description of the relation of brain to mind in a concise fashion:

Some modern philosophers have recognized the distinctions portrayed in my Fourier diagram as Cartesian and Heisenbergian “cuts.” In keeping with the spirit of Cartesian co-ordination, I prefer to characterize the relationships between the distinctions as *dependencies* rather than cuts. As one of my undergraduate students eloquently put it: “*The mind-body relationship is much less of a ‘problem’ than it is a joyous ‘harmony.’*”

The Cartesian, up-down relationship in the diagram describes a dependency between communication and the physics of matter: A material medium is required for a communication to take place; and the physics of matter is described in mathematical, mental terms. The Heisenberg left-right dependency describes uncertainties in precisely specifying transformations between the spectral and space-time domains.




*94.*

Thus the diagram has two axes, an up-down and a right-left. Each axis describes a transformation, a change in coordinates. The left-right distinction in my Fourier diagram—between a potential world of spectral flux and the space-time world as we experience it—as noted, is called the "Heisenberg dependency" because Werner Heisenberg showed that there is a limit to how accurately we can simultaneously measure the momentum and the location of a mass. The physics community, which was accustomed to accurately measuring whatever was of interest, had to realize that there can be a residual uncertainty in some measurements in some situations. Gabor showed a similar limit in simultaneously measuring the pitch aspect of a communication and its duration. But as we shall shortly see, the diagram shows that we need to seriously consider not only the reduction of uncertainty measured as information but also the *pre-existing uncertainty* upon which the reduction is based. I'll have more to say on this important topic in the next chapter.

## When Matter Doesn't Matter

The definitions and measurements of energy and entropy were formulated during the 19th century when steam engines were invented and it was essential to be able to measure how much work the heat produced by an engine could do and how much of that work was dissipated (as by friction or vaporization). The science of measuring and understanding energy and entropy is known as "thermodynamics."

The up-down dependency shown in my Fourier diagram distinguishes change from inertia. The upper part of the diagram focuses on change as it occurs in both energy and entropy, defined as follows: Energy is commonly measured as the numerical amount of actual (kinetic) or potential work necessary to change a process. Entropy is a numerical measure of how efficiently that change is brought about.

During the 20th century, with the advent of telephones and computers, it became important to measure the energy requirements of systems of communication and computation. As with the steam engine, the issue of efficiency of operation was considered critical. How much of a message is lost in communication? How "efficient" is a computer program: that is, how much computer time and space does it take to make the required computation?

Claude Shannon, working at the Bell Laboratories in the late1940s, formulated a numerical answer to these questions in terms of switches: How many of the switches in a telephone exchange or in a computer's hardware are in an "on" position and how many are in an "off" position? Accordingly, the unit of measurement was made in terms of the number of "on and/or off" positions and became the "bit" (binary digit).

Surprisingly, Shannon's equations had the same *form* as those that had been used to describe entropy in thermodynamics. Shannon therefore suggested that the measure of an amount of uncertainty in a communication is formally the same as the amount of entropy in a thermodynamic process. Reducing that uncertainty provides the information in the communication. The amount of reduction of uncertainty provides the measure of the amount of information that has been communicated. Shannon's measure of the reduction of uncertainty was shown by Gabor to be related to his measure of minimum uncertainty, which he based on what he called "selective entropy." Although there have been arguments about the validity of making comparisons between thermodynamic and communication theory, here we are discussing the patterns, the *form* or formulations of the theories, not their applications.

Shannon's formulation allows us to define precisely Descartes's "cogito," thought, in terms of communication theory. John Dewey, the educator and pragmatist, noted in *The Natural History of Thinking*: "The man in the street, when asked what he thinks about a certain matter, often replies that he does not think, he knows. The suggestion is that thinking is a case of active uncertainty set over against conviction or unquestioning assurance.” Shannon’s definition of information as the “reduction of uncertainty” thus provides us with at least one scientific measure of the thought process.

Note that in these descriptions there is no mention of mass. In thermodynamics and in communication one might say: Matter doesn’t matter—or, as we shall see shortly, it matters only as a medium for the manifestation of energy and the medium for communication.

## On the Other Hand, in Physics . . .

Contrast this to the lower part of the Fourier diagram: the inertia of a mass is defined as its momentum, the force that resists change. When the comfort of the constant momentum of your car is suddenly altered in a crash, the potential force of the momentum becomes activated. Just as energy has a potential and a kinetic form, so does momentum.

Position involves mass: The location of a shape, a mass (such as yourself) can be mapped onto a system of coordinates. For example, you are sitting in your car listening to the CD version of this book, happily unaware of the speed of rotation of the earth around its axis. Despite these gyrations, you are able to locate yourself with a Global Positioning System.

## Flux and Space-Time

The left-right dependency on my diagram serves to distinguish between observations made of the spectral domain and those made in space and time. The spectral domain is characteristically a *flux*, composed of oscillations, fluctuations, where interference patterns among waves intersect to reinforce or cancel. Holograms are examples of spectra, that is, of a *holo-flux*.

As described in Chapter 2, flux can be visualized by removing the lens from a projector showing a slide—and using ordinary eyeglasses to demonstrate the spread of the “information” in the slide over the whole illuminated field. Flux describes potential energy and momentum. Since flux is potential, we cannot measure it—until the energy becomes kinetic. The potential energy and momentum in a mountain lake are not realized until its water flows out to form a waterfall. Then its efficiency and mass of the waterfall can be measured.

Only through their manifestations in space and time do we get to know of the existence of potentials such as those of energy, of momentum, and of holographic processes. We can know the potential domain only by way of realization in space and time—a dependency between the potential and the world we navigate. Both in physics (Heisenberg) and in thermodynamics (in the concept of free energy) some uncertainty arises when this dependency is subjected to precise measurement.

In the communication sciences, a similar relationship has been established. Gabor called his wavelets “quanta of information.” He related Shannon’s measure of uncertainty to the Heisenberg formulation of indeterminacy for the limit of simultaneous measurements of momentum and mass. Gabor showed such a minimum to exist for communication: the minimum uncertainty that can characterize a message—that is, the maximum compressibility that a message can achieve and still be interpretable. In communication, therefore, as in thermodynamics and in the physics of matter, the form of the Fourier relation holds.

# Communication and Matter

The up-down dependency in the diagram illuminates a different aspect of our understanding: We have come to realize that physics and psychology are inter- dependent sciences. To communicate (minding) we must embody the communication. Likewise, we cannot understand the physics of matter without recourse to communication, to minding.

To illuminate this important point, let me begin with a story: Once, Eugene Wigner remarked that in quantum physics we no longer have observables, only observations. Tongue in cheek, I asked whether that meant that quantum physics is really psychology? Instead of the gruff reply that I’d expected, Wigner beamed me a happy smile of understanding and replied, “Yes, yes, that’s exactly correct.”

If indeed one wants to take a reductive path in science, one ends up with observations, with psychology, not with observables such as particles which remain unchanged, that is invariant, over many different ways to observe them. In fact, it is *mathematics, a psychological process,* that describes the relationships that organize matter: *current physics is thus rooted in both matter and mind*.

The converse story to the one that describes physics is the situation in communication. Communication ordinarily occurs by way of a material medium such as air, water, or wire. Bertrand Russell noted that the form of a medium is largely irrelevant to the form of the communication that is mediated by that medium. With respect to the relation among brain/behavior/experience, *the medium is not the message*. In terms of what philosophers and computer scientists call functionalism, it is the communicated form of a *pattern* that is of concern, *not the shape* of the material that conveys the pattern. The shape of the medium can be as disparate as that of a cell-phone, a computer, or a brain in a human body. But the functionalist story is incomplete: *not to be ignored is the fact that communication depends on being embodied in some sort of material medium and that embodiment demands a particular know-how, particular sets of transformations to accomplish the embodiment*.

One way we may interpret the dependencies between communication and matter is that *mass is an "ex- formation," an externalized (extruded, palpable, concentrated) form of flux*. In the same vein, *communication (minding) is an "internalized" forming of flux, its "in-formation.*"

Bernard d'Espagnat, a theoretical physicist, in his treatise *In Search of Reality* summarizes a similar view:

> *It is thus quite legitimate to perceive in the whole set of consciousnesses, on the one hand, and in the whole set of objects, on the other hand, two complementary aspects of reality. This means that neither one of them exists in itself, but that each one comes into existence through the other . . . Atoms contribute to the creation of our eyes, but also our eyes contribute to the creation of atoms . . . . [I]ndependent reality is situated beyond the frames of space and time—empirical reality, that of particles and fields, is, like consciousness [cogito] merely a reflection of independent reality.*

d'Espagnat's "independent reality" is described by me as a holo-flux, that is, as "potential reality; his "empirical reality" is characterized in my approach as "experienced reality."

Thus, taking Descartes's *total* enterprise, the Cartesian distinction between thought and matter and *their union in mathematics and everyday life*, leads, to *"complementary embodiments": "a joyous harmony" of the meaning of the mind-brain relationship*.

My experiments described in the next chapter show that Shannon's "information measurement as the reduction of uncertainty" provides us only a beginning in our ability to understand the multiple embodiments of mental processes. The patterns of pre-existing uncertainty need to be *specified* and *sampled* as well. My suggestion is that such sampling can be used as a measure of meaning.

# Chapter 25
## Meaning

Brain scientists need to be concerned with meaning, not just information processing. Herein, I chart an experimental approach to brain processes as they organize meaning.

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> *One has the vague feeling that information and meaning may prove to be something like a pair of canonically conjugate variables in quantum theory, they being subject to some joint restriction that condemns a person to the sacrifice of the one as he insists on having the other.*
>
> —Claude Shannon and Warren Weaver, 1949

## The Meaning of Information

The ability to quantitatively measure "information" was such a breakthrough in our ability to understand communication and computation that scientists felt that little else needed to be achieved. But we were wrong. As we began to test the theory in live organisms instead of artifacts such as telephones and computers, we found the theory woefully inadequate. The problem was, and is, that in ordinary communication between live organisms we have to specify what is meant by the "amount of uncertainty" which needs to be reduced in order to achieve a measure of an amount of information. And *your* uncertainty may not be *mine*.

Despite this, current neuroscientists continue to speak of "information processing" in its more popular usage to encompass "meaning." This has the disadvantage that it fails to formulate a neuroscience of meaning in its own right. As noted in the quotation from Shannon that introduces this chapter, such a formulation may be achieved by analogy to measurement in quantum physics: *measuring meaning is most likely to be complementary to measuring information as uncertainty reduction*.

A neuroscience of meaning can fruitfully begin, as noted in earlier chapters, with Charles Peirce's definition: meaning is what we mean to do—to which I added that meaning is also what we mean to experience. The current chapter describes the experiments and their results that lead me from the theory of information processing to an equally rigorous theory of meaning.

## An Experiment

In the late 1950s, I designed an experiment, using monkeys, to test information measurement theory. I planned to see which part of the brain is involved in our ability to choose among alternatives—the number of alternatives specified by the amount of "Shannon information" in each choice. My plan was to set up a board that had twelve holes, each large enough to hold a peanut. I went to the dime store and picked up twelve junk objects just large enough to cover the holes. I wanted to test the monkeys' ability to find a peanut hidden under one of the objects displayed, given a display of two, three, four, etc. objects from which to choose. The idea was simple: the more objects (alternatives), the more trials (or the longer) it would take the monkey to find the peanut.

No one had tried to work with monkeys using such a large number of simultaneously displayed choices. On preliminary tests, I found that untrained monkeys simply refused to work with large displays, given so much "uncertainty," such a paltry chance of finding a peanut. I had to train the monkeys by starting with a choice between two objects and working up to twelve. To keep the monkeys working, I kept the prior set of objects intact, though in different placements on each trial. Two years of testing twelve monkeys, four hours each day, in what came to be called the "multiple-choice experiment," provided some unexpected results: When there were fewer than four cues to choose from, the monkeys behaved differently than they did when there were more than four cues. The cut-off point at four indicates that animals (and humans) can immediately tell which alternatives are to be considered. This ability is called "subatizing." With more than four alternatives, a search becomes necessary.

Rather than searching randomly—as would have been ideal for my experiment if I had been able to vary the number of cues that I presented—the monkeys learned to search for the peanut through the array of objects I had used on previous trials. Thus, for them, the ability to remember which objects had been most recently rewarded was the issue—not a choice among the several, up to twelve, cues. For the monkeys, the problem had become something very different from the one that I had set out to test.

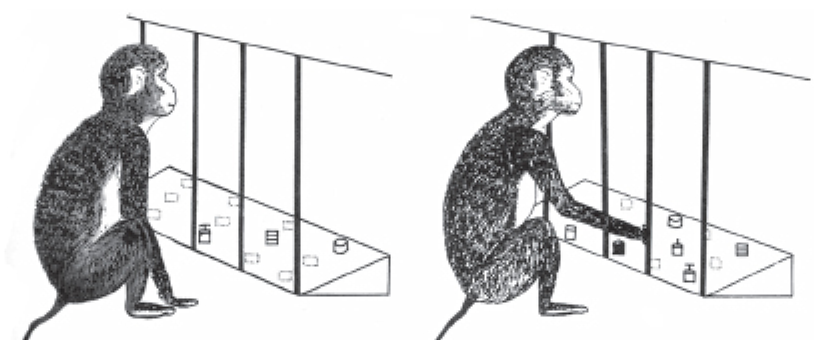


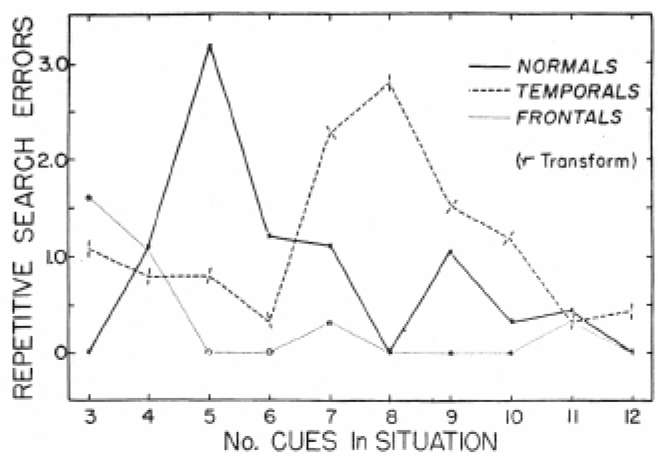
FIG. 1 FIG. 2

*95. Figuress 1. and 2. Diagram of the multiple object problem showing examples of the three and the seven object situations. Food wells are indicated by dashed circles, each of which is assigned a number. The placement of each object over a food well was shifted from trial to trial according to a random number table. A record was kept of the object moved by the monkey on each trial,* *only one move being allowed per trial. Trials were separated by lowering an opaque screen to hide, from the monkey, the objects as they were repositioned. (From Pribram, "On the Neurology of Thinking"* Behavioral Science*)*

This experiment was set up to examine the effects of restricted removals of different areas of the brain cortex on information-processing ability when I made restricted removals of different areas of the brain cortex. I used four monkeys for each area removed and found that removal of one specific brain area, the inferior temporal cortex, and no others, changed the way the monkeys searched for the peanut. I was puzzled by the result: The control monkeys took progressively more search trials as the experiment proceeded—but not in the way information measurement theory had predicted. Even more puzzling, the monkeys with removals of the inferior temporal cortex actually did *better* than the unoperated and operated control monkeys during the early parts of the experiment, a result which was opposite to any that I or anyone else had found before. As is my custom when I can't understand an experimental result, I presented these findings (along with others that I *did* understand) in talks given on various occasions—and asked the audience whether anyone did have an explanation.

## An Explanation

On one of these occasions, at Dartmouth, a young professor, Bert Greene, made a suggestion which could be tested by reanalyzing the data: Greene predicted that the animals with the brain operations differed in the way they sampled the displayed cues. (Sampling meant that the monkeys moved the cue to see whether there was a peanut in that well.) His prediction was correct. Whereas normal monkeys tended to return to cues that had been



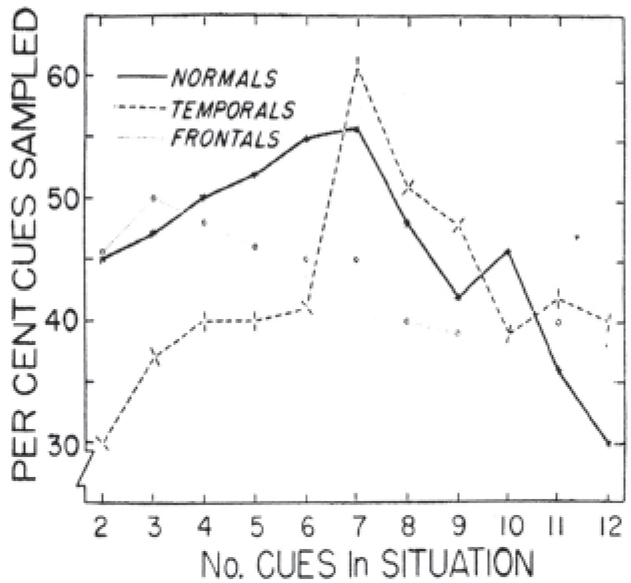

*96. Graph of the average of the number of repetitive errors made in the multiple-object experiment during those search trials in each situation when the additional, i.e., the novel, cue is first added.* rewarded previously, the monkeys with the brain operations sampled the displayed cues randomly. The brain surgery had removed a memory process that the control monkeys used in making their choices.

I was able to show that mathematical sampling theory described quantitatively what was happening. Sampling theory predicted the change in behavior at the four-cue point in my experiment and fit the data obtained throughout. I had started to test information measurement theory and ended up testing mathematical sampling theory instead!

From this “multiple-choice experiment” I learned something that other experimental psychologists were also learning at the time: if we are to measure Information in terms of the reduction of uncertainty, we must know the subject’s state of uncertainty. My monkeys responded to the alternatives, the available choices presented by the display, not as a straightforward series from 2 to 12 but as an array to be sampled in which previous responses were remembered. As Ross Ashby noted, we learned that information measurement theory was a superb instrument for framing issues but not helpful when the subject in an experiment was working within a context, the measure of uncertainty not accessible to the experimenter.

## What Is Being Sampled

In another, somewhat simpler experiment, I taught two groups of monkeys (four in each group) to choose one of two objects: a *tobacco tin* and an *ashtray*. One group of monkeys had received a removal of the inferior temporal cortex in both hemispheres of their brains; the other group served as control subjects who had not been operated upon. Monkeys with the cortical removals took somewhat longer to learn to make such a choice—for example, to choose the




*97. Graph of the average of the percent of the total number of objects (cues) that are samples by each of the groups in each of the situations. To sample, a monkey had to move an object until the content or lack of content of the food well was clearly visible to the experimenter. As was predicted (see text), during the first half of the experiment the curve representing the sampling ratio of the posteriorly lesioned group differs significantly from the others at the .024 level (according to the non-parametric Mann-Whitney U procedure, [Mann & Whitney, 1947].) (From Pribram, "On the Neurology of Thinking'"* Behavioral Science*) ashtray*—when compared to the number of trials it takes normal animals to learn to make that choice.

After the monkeys had learned to make the choice, I changed the situation in which the choice had to be made. Now, I placed either the ashtray *or* the tobacco tin in a central place between two wells covered with identical lids. The task for the monkeys was to find the peanut: the peanut was always in the well on their right in the presence of an *ashtray*, and in the well on their left when a *tobacco tin* was present. This was a difficult task for a normal group of monkeys to learn—it took them around 500 trials to do so. But the monkeys who had the cortex of the inferior temporal lobe removed failed to learn to make the correct choice in this task in several thousand trials.

To assure myself that the monkeys who were failing were still able to "tell the difference" between the *ashtray* and the *tobacco tin*, I inserted ten trials of the original task where both ashtray and tobacco tin were present during the opportunity for choice. Invariably, all monkeys made the choice that they had learned earlier on all ten trials. *The failure on the new and difficult task was not in perceiving a difference between the stimuli but in navigating the world of the new, more complex situation—the context—in which the choice had to be made*. The lesson for me was, once again, it's not the sensory information that is being processed but the *meaning that is given* to that information *by the context* in which it is being processed.

## The DADTA

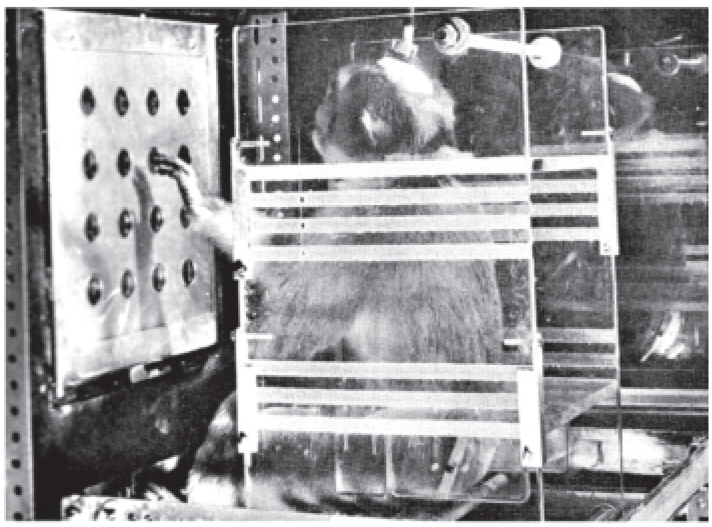
Rewarding as the result of the multiple-choice experiment was, I realized that no one in his or her right mind (including me) would ever undertake to repeat such a multi-year-long, drawn-out, tedious testing procedure. Laboratory-friendly computers were just coming on the scene in 1958 as I was moving to Stanford, so I resolved to computerize my laboratory at Stanford. I designed and had the Stanford Research Institute build a special-purpose device that was based on telephone-switchboard-controlled automated behavioral testing equipment. For the first apparatus, peanuts were placed in a vertically mounted roulette wheel. The mechanical driver of the wheel made such a racket that it scared not just the monkeys who were to test in it but also the entire laboratory.

Nonetheless, I demonstrated the device at the convention of the American Psychological Association that year with the help of the single adult male macaque monkey who was not frightened by the noise. The demonstration was a complete success; it attracted a large crowd, and my stalwart simian subject and I got a kick out of watching the reactions of the crowd.

Returning to Stanford, I arranged to have a more civilized apparatus built, again by the Stanford Research Institute, and named it DADTA, an acronym for Discrimination Apparatus for Discrete Trial Analysis. The original special-purpose machine was soon replaced with a general-purpose computer whose specifications I helped set up—I received the third and seventeenth ever built. Within a decade, my students and I were training 100 monkeys a day on three DADTA in a totally computerized laboratory: the task displays and reinforcing contingencies were programmed and the monkeys' responses were recorded by the small general-purpose computers which, by then, we also used to study brain electrical activity recorded with microelectrodes.

## Monkeys Can't Think?

I wrote up my results under the title "On the Neurology of Thinking." The history of its route to publication is one of those sagas that keep young investigators from innovating. I had been asked in 1958 to write a "lead article" for publication by the journal *Science* and felt the findings in my multiple-choice experiment to be sufficiently novel to be worthy of this prestigious publication.



*98. Brain and Perception*

In the introduction I noted that the paper was about only one kind of thinking, that is, problem solving. The paper presented the data (including the mathematics in a footnote) and noted that there were two aspects to problem solving: one, the amount of information, that is the amount of uncertainty reduction; and two, the specification of uncertainty, the context within which the reduction was taking place.

Despite the fact that I had been invited to write the paper, it was summarily rejected. Reasons: "Everyone knows that monkeys can't think; the paper does not reflect established views." My response: "I had stated that I had limited my paper to that aspect of thinking known as problem solving. The data showed that the monkeys were capable of problem solving. The monkeys had demonstrated active uncertainty by tentative responses—scratching their ears and stroking their chins and by the longer time it took them to respond when there were more cues to choose from." I had started the paper with a quotation (noted in the previous chapter) from the pragmatist, John Dewey, who wrote in *The Natural History of Thinking*:

> *The man in the street, when asked what he thinks about a certain matter, often replies that he doesn't think at all; he knows. The suggestion is that thinking is a case of active uncertainty set over against conviction or unquestioning assurance.*

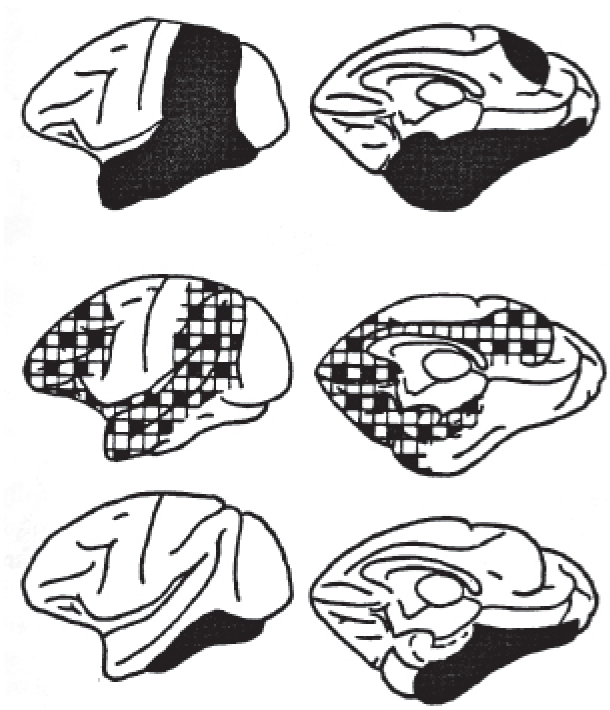
It took two more decades before the "established views" reflected what is common knowledge: the fact that animals do problem-solve and show signs of being thoughtful while doing so. Have you ever tried to place a bird feeder in a place inaccessible to squirrels?

In 1959, I sent the paper, "On the Neurology of Thinking" to a relatively new journal, *Behavioral Science*. The editor and reviewers were laudatory and the paper was accepted for publication within a few weeks.

## Sensory Specificity in the "Association" Cortex

The results of the "multiple-choice experiment" fit with others that I obtained in a long series of studies in which I removed areas of cortex from the back of the monkeys' brains. These areas were at that time called "silent areas" because brain electrical stimulation had no effect, and surgical removals in behavioral studies had not resulted in any consistent changes in behavior. This cortex is also called the "association cortex," so named, in the latter part of the 19th century, by Viennese neurologists (especially Flechsig and Meinert, teachers of Freud) who were philosophically aligned with "British associationism." These neurologists suggested that the cortex that lies between the primary cortical sensory receiving areas serves to combine, to "associate" visual, auditory and tactile sensations with one another to produce higher-order cognitions. They thus named this reach of cortex the "association cortex." If it has a name, it must exist as such!

Contrary to the accepted view at the time, research conducted in my laboratory consistently showed that the silent cortex included systems that *are* sensory specific. That is, surgical removal restricted to one or another part of this cortex influences behavior in one sensory modality only; and further, that higher-order processing in general includes several steps that involved only one sense at a time. For instance, these experiments showed that making choices among visually presented objects is altered when, and only when, an area of cortex in the temporal lobe is removed. When an area in the parietal lobe is removed, the perceptual difficulty is limited to reaching. Another part of the temporal lobe is involved in making auditory choices; and farther forward is the system that is involved in making choices among tastes.



*99. The upper diagrams represent the sum of the areas of resection of 15 subjects showing a decrement in the performance of a pre-operatively learned visual discrimination task. The middle diagrams represent the sums of the areas of resection of 25 subjects showing no such decrement. The lower diagrams represent the intercept of the area shown in black in the upper and that not checkerboarded in the middle diagram. This intersect represents the area invariably implicated in visual choice behavior by these experiments. (From: Pribram, "Neocortical Function in Behavior. Invited" Address to the Eastern Psychological Association, 1955.)*

Such sensory-specific higher-order effects had been known to be present in humans who have suffered damage in these brain areas. But it was commonly thought that the specificity was due to intrusion of the damage into adjacent primary sensory systems. My experiments were designed to avoid such intrusions and showed them not to be responsible for the sensory specificity. After many publications over many decades, these results have become accepted as common knowledge.

In addition to these publications were some contributed by Mortimer Mishkin (a former doctoral and postdoctoral student) and Leslie Ungerleiter who, as a postdoctoral student, had published with me (as discussed in Chapter 6 on objects and images) the results of the study that showed size constancy to be impaired by resections of the peri-striate cortex in monkeys. Their influential publications developed the theme that visual processing became divided into two pathways, one through the parietal lobe of the brain that computed the location of an object (its "where") and the other through the temporal lobe that specified the nature of the object (its "what"). Further research showed that the parietal pathway is composed of a short ventral path that processes where an object is located as well as a more extended dorsal branch that processes how an object comes to be used.

I expressed (and published) several caveats that need to be kept in mind: 1) Ungerleiter's and my studies, as well as those of others, indicated that the prestriate cortex was especially involved in object constancy—the fact that objects are objects irrespective of the perspective from which they are perceived; 2) that the entire posterior parietal and temporal cortex are involved in the processing of spatial relations, as shown by Charlie Gross; and 3) the pathways are not cortico-cortical pathways since carefully controlled extensive removals of the cortex lying between the primary visual cortex and the parietal and temporal cortex did not alter the functions of the pathways. Rather, the connections dip down through the thalamus and basal ganglia and back up again in various locations.

Once these "pathway" studies were published, a virtual cottage industry developed to study the anatomy, physiology and behavioral relationships of visual processing forward of the primary visual receiving cortex. The results of this outpouring of results are elegantly reviewed and summarized (in *The Tell-Tale Brain: A Neuroscientist's Quest for What Makes Us Human*)—as is their relevance to cases of human brain pathologies. And most important: the author V. S. Ramachandran emphasizes and shows how these parts of the brain deal with meaning.

Meaning depends on another caveat that these studies do not take into account. I pointed out to various contributors to my 1974 section of the Neurosciences Third Study Program meetings entitled "Central Processing of Sensory Input” that all these “pathways” are reciprocal; that is, there is as much “traffic” going from the higher-order parietal and temporal lobes (and most densely from the peristriate cortex) to the primary visual cortex as there is emanating from that cortex. It is these centrifugal influences from higher-order systems onto the primary sensory and motor systems that are responsible for generating meaning.

A corollary to this insight is that, as I teach my students, we live in our sensory-motor systems. It is in these systems that the input from the world we navigate and that from our central brain processes comingle. We as often introject as project the result, especially in complex situations.

It is the job of psychotherapists to “locate” what is going on.

## Two Meanings of Meaning

Further, as shown in humans by Martha Wilson, then professor of psychology at the University of Connecticut, who had been one of my students, comprehension of meaning is of two sorts: 1) choosing on the basis of *the use an object can be put to*, which is related to the functions of the left hemisphere of the brain; and 2) choosing, based on *the physical (perceptual) attributes of an object,* which is related to the functions of the right hemisphere.

Alex Martin has made a comprehensive review (*Annual Review of Psychology*, 2007) of his own findings and those of others using the fMRI technique of imaging the activity of ongoing brain processes in humans. He has fully confirmed not only most of what is in this chapter but also Martha Wilson’s localization of the two sorts of comprehending.

The two ways of comprehending reflect the two ways of attaining meaning, noted earlier: I mean by “meaning” what I mean to do and what I mean to experience. In both senses, meaning entails choice.

## Comprehension of Meaning

What these studies showed is that not only the perception of objects, but also comprehending their meaning is processed by sensory-specific systems of the brain. But comprehension can be described by information measurement theory *only* if the context (the uncertainty) in which the description occurs is specified. The *meaning* of the information depends on clearly describing a context (the uncertainty) and the sampling, *an active selecting*, of forms within that context.

In an excellent interchange with the students of my 2008 autumn semester class at Georgetown University, something became clarified that I had not fully comprehended. Comprehension, as it depends on an active selecting of forms within the context (the uncertainty) of information processing, is dependent on "attitude." Attitudes are formed by processing novelty. Novelty deals with arrangements of patterns that can be described in terms of the structure of redundancy. Thus, the context of information processing is described in terms of the non-linear dynamics of complexity.

*Information processing theory deals with the amount of information, the number of distinctions processed by the immediate brain systems involved with the input from the world we navigate; complexity theory deals with the choices, initiated by our world within, that we use when we navigate our world.*

A summary of the results of these experiments can be stated succinctly: *The processes that occur by virtue of the brain systems beyond the primary sensory and motor systems are best described by sampling theory, that is, processing choices among the physical attributes of a perceived object or the use to which that object can be put. These choices are guided by the attitudes we bring to the way we navigate our world.*

*The time has arrived to acknowledge "meaning" and its basis in active choice among perceptual and useful forms as a precisely definable concept in the psychological and brain sciences. Such a science of meaning would provide a venue for a rapprochement with the humanities thus bridging the now existing gap between these "two worlds" of inquiry.*

# Appendix A
## Minding Quanta and Cosmology

Karl H. Pribram, MD, PhD (Hon. Multi.)

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*Physical concepts are free creations of the human mind and are not, however it may seem, uniquely determined by the external world.*

—Albert Einstein and Leopold Infeld, 1938

# Minding Quanta and Cosmology

*The revolution in science inaugurated by quantum physics made us aware of the role of observation in the construction of data. Eugene Wigner remarked that in quantum physics we no longer have observables (invariants) but only observations. David Bohm pointed out that, were we to look at the cosmos without the lenses of our telescopes, we would see a hologram. I have extended Bohm's insight to the lens in the optics of the eye. The receptor processes of the ear and skin work in a similar fashion. Without these lenses and lens-like operations all of our perceptions would be entangled as in a hologram. Furthermore, the retina absorbs quanta of radiation so that quantum physics uses the very perceptions that become formed by it. In turn, higher-order brain systems send signals to the sensory receptors so that what we perceive is often as much a result of earlier rather than just immediate experience. This influence from "inside-out" becomes especially relevant to our interpretation of how we experience the contents and bounds of cosmology that come to us by way of radiation.*

# Introduction

The revolution in science inaugurated by quantum physics made us aware, as never before, of taking into consideration the role of observation and measurement in the construction of data. A personal experience illuminates the extent of this revolution. Eugene Wigner remarked that in quantum physics we no longer have observables (invariants) but only observations. Tongue in cheek, I asked whether that meant that quantum physics is really psychology, expecting a gruff reply to my sassiness. Instead, Wigner beamed a happy smile of understanding and replied: "Yes, yes, that's exactly correct." In a sense, therefore, if one takes the reductive path in science one ends up with psychology, not particles of matter.

Another clue to this "turning reductive science on its head" is the fact that theoretical physics is, in some non-trivial sense, a set of esthetically beautiful mathematical formulations that are looking for confirmation (see George Chapline 1999, "Is theoretical physics the same as mathematics?").

At a somewhat more conservative level, Henry Stapp (1997/1972: The Copenhagen Interpretation) has eloquently reviewed the history of how the founders of quantum physics (e.g., Niels Bohr, Werner Heisenberg, John von Neuman,) dealt with the then newly realized importance of the "how" of our observations to an understanding of the composition of matter. Stapp has added his own views on how these innovations in thinking affect our understanding of the mind/ matter interface.

Here I will pursue a different take on the issue: coming from brain science, how can we better understand some of the puzzles that have plagued quantum theory and observation to the point of "weirdness"? And furthermore, how important are the prejudices of our Zeitgeist in interpreting our cosmological views? My hope is that by pursuing the course outlined here, weirdness and prejudice will, to a large extent, become resolved.

## Observing Quanta

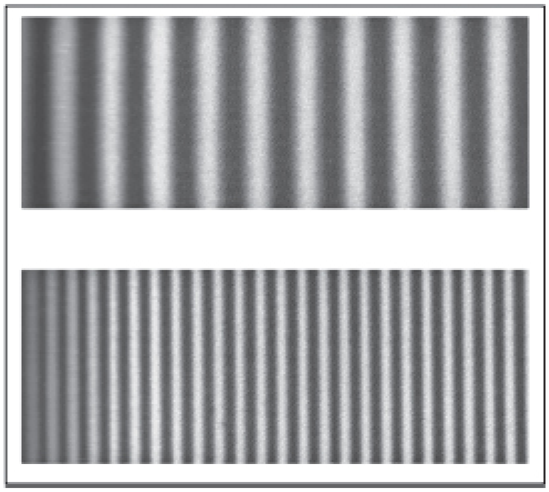
To begin: David Bohm (1973) pointed out that were we to look at the cosmos without the lenses of our telescopes, we would see a hologram. Holograms were the mathematical invention of Dennis Gabor (1948), who developed them in order to increase the resolving power of electron microscopy. Emmet Leith (Leith and Upaticks 1965) developed the hologram for laser light photography, a development that has, in popularity, overshadowed the mathematical origin of the invention. Holography is based on taking a space-time image and spreading it (the transformation rule is called a spread function; the Fourier transformation is the one used by Gabor) over the extent of the recording medium. Thus, the parts of the image have become wholly enfolded with each other and the whole has become totally enfolded in each part.

*100. Eugene Wigner's 80th Birthday*

I have extended Bohm's insight of the importance of lenses in creating a space-time image to the lens in the optics of the eye (Pribram 1991). In fact, the receptor mechanisms of the ear, the skin and probably even the nose and tongue work in a similar fashion. Without these lenses and lens-like operations all of our perceptions would be enfolded as in a hologram.

In optics, a very small aperture of the pupil produces the same transformation as does a lens. When the pupil has been chemically dilated as during an eye examination, focus is lost and the experienced vision becomes blurred. However, if a pinhole or slit in a piece of cardboard is placed in front of the dilated eye, ordinary vision is restored. One can accomplish this in a crude fashion if one needs to read some directions by tightly curling one's index finger producing a slit. Also, in experiments during which we map the receptive fields of cells in the brain, we drift dots or slit-like lines and edges in front of a stationary eye. In my laboratory we used dots, single lines, double lines and gratings and found differences in the recorded receptive fields when more than one dot or line was used. The differences were due to interactions produced in the visual system of the brain when the stimulating dots or lines moved together against a random background.

What I'm proposing is that the difference in the observation of interference effects (an enfolded holographic record) in the two-slit experiment vs. the observation of a granularity (particles) in the single-slit experiment is due to the difference in the measurement apparatus. This, of course, is not a new proposal: it is the essence of the argument made initially by Bohr and accepted by quantum physicists for almost a century. What I am adding is that the measuring apparatus, the slits, are mimicking the biology of how we ordinarily observe the world we live in. There is no weird quantum effect unique to that scale of observation.



*101.*

## The Brain's Role in the Making of Observations

In turn, the observations made in quantum physics are relevant to how we perceive our world. The retina of the eye has been shown to absorb a single quantum of photic energy: that is, the retina has a resolving power such that it consists of pixels of single quantum dimension. Yakir Aharonov has developed an experimental paradigm for quantum physics that he calls "weak measurement." Weak measurement does not disturb what is being observed. Essentially, the technique consists of repeated measurements composed of two vectors, a "history" vector determined by past events and a "destiny" vector determined by events that occur in the future of the time any single weak measurement is obtained. I noted that this apparently startling procedure is similar to the one used in non-linear dynamics (complexity theory) that traces the vectors that develop what have been called "attractors" over repeated observations of paths toward stabilities far from equilibrium. Point attractors and periodic attractors are two simple examples of such stabilities.

Research in my laboratory established functional pathways that connect higher-order cortical systems to the retina. Eight percent of the fibers in the optic nerve are efferent to the retina, and these fibers are able to change retinal processing about 20% of the time. The control of the retina occurs within the time that retinal processing of optical input occurs.

Thus, whenever there is a repetition of a sequence of optic inputs, a second vector "anticipating" that input is operative. Just as in quantum physics, "attractors," *contextual futures determine our visual perceptions* —and what is true of vision has also been shown to be true for hearing, tactile and kinesthetic perceptions and the perception of flavors.

The laws of physics, especially the laws of quantum physics, apparently have their complement in the laws of human perception: The laws of quantum physics have been shown to be dependent on the constraints imposed by the instruments of observation. The laws of human perception have been shown to be dependent on the constraints imposed by processes such as attention, intention and thought organized by the observer's brain. To complete the hermeneutic cycle, observations in physics are made by humans whose observations are dependent on their brains.

# Meaning

Patrick Heelan discusses at length the transition of scientific, philosophical and religious thought from a separation of our perceptions from an "out there," to an interpenetrating, intentional, view of a meaningful reality. Heelan indicates that this transition comes by way of the hermeneutic process that stems from individual encounters in the world we navigate. This view is considerably more sophisticated than the currently accepted way of describing the organization of brain function and of communication in terms of "information processing."

The popularity of "information processing" has two sources. One source is that when speaking of "information" most people mean meaningful information. The other source comes from communication theory and its use in telephony and computer science. Claude Shannon defined "information" as the "reduction of uncertainty" and sharply separated this definition from the definition of "meaning." The usefulness of Shannon's definition has given "information" an aura of respectability that has been assimilated by the undefined use of the term "information processing." Actually, the more appropriate term would be the "processing of meaning" but then we would need a scientifically useful, that is testable, definition of "meaning."

A good beginning can be made with Charles Saunders Peirce's definition: "What I mean by meaning is what I mean to do." Coming from one of the founders of pragmatism this is hardly surprising. I would add: "What I mean by meaning is what I intend to do *and what I intend to experience*."

These are good beginnings but do not provide us with the useful laboratory testable procedures that make the concept "meaning" as transparent as Shannon's (and Gabor's) concept of "information." In order to provide such a transparent concept we need to take a detour to define a context for Shannon's definition of "information" and then show the shortcomings of Shannon's definition for human (and primate) communication. Finally, we need to describe an experimental result that provides at least one definition of "meaning."

This detour is relevant to our interpretation of quanta and cosmology. For decades, quantum physicists were divided as to the best representation of quantum phenomena. Schrödinger, DeBroglie and Einstein opted for the wave equation while Heisenberg, Bohr and his Copenhagen adherents opted for a vector representation of quantum "reality." I recently published a paper in which the results of micro-electrode analysis of brain processes was shown both in terms of wave functions and vectors. In that paper I recapitulated the quantum physicists' arguments: the wave representation is more "physical" more "*anschaulich*"; the vector representation is more abstract and therefore can be more easily applied over a range of experimental results. What I am proposing is a way of conceptualizing the brain/ mind relationship (or better stated, the person/experience relationship) that is derived from, and in turn, motivates our understanding of quantum physics.

# The Holographic Process

The precision of our understanding is today best formulated in mathematical concepts. The root problem in coming to grips with the person/experience relationship, the brain/mind transaction, is that at first blush, brain is material, matter, while what we experience is different. We can eat brains but not our experience. The current way scientists deal with experience is in terms of communication and computation, in terms of information processing. But any more human approach to the issue finds "information processing" barren. Additionally, as noted, the manner in which scientists use "information processing" is itself largely unscientific.

These limitations of understanding brain and mind, person and experience, need not be so. Careful attention to what philosophers have had to offer since René Descartes, what the science of radiation (heat and light) has shown, what psychologists and communication sciences have developed, can provide a transparent set of concepts that go a long way toward "resolving" this apparently intractable problem.

The formation of attractors during our experiencing the world we navigate (and in performing experiments) is a complex dynamic process. In order to examine aspects of this process in detail, sections (Poincaré sections), slices, can be taken at any "moment" to display this complexity. One such momentary display is the holographic experience.

Experiencing a holographic process at the macroscopic scale is just as weird as any observation made in quantum physics: My classroom demonstration always evokes disbelief. I take an ordinary slide projector and show a slide (for example, a pastoral scene). I then take the lens of the projector away, and as predicted by Bohm, all one sees is a fuzzy cone of light containing no discernable image. Then I take a pair of reading glasses and hold it in front of the projector at just the right distance. Voilà! *Wherever and whenever* the lenses focus the light, the image on the slide (the pastoral scene) appears. Taking two pairs of spectacles, one can demonstrate four images—and continue to show images anywhere there is light. In experiments performed in quantum physics, a pinhole or single slit is the equivalent of the lens in the classroom experiment. At the quantum scale, replace the pastoral scene with a particle. The "particle's" holographic form (its complex conjugate) becomes exposed by means of double or multiple slits (gratings). The "scenic" particle is now spread *everywhen and everywhere*.

This holographic form of holism is not to be confused with the hierarchical form in which the whole is greater than and different from the part. Hierarchical relations are found everywhere in biology and in the behavioral sciences. The holographic form of holism has come into science fairly recently. The spectral aspects of quantum physics and the procedures used in functional Magnetic Resonance Imaging (fMRI) and in digital cameras are examples. However, in optics, interference effects have been studied since Huygens, though their importance to our understanding of brain and cosmos had to await the insights of the 20th century.

# The Brain's Role in the Making of Theories

Brain science can contribute even more to our understanding of quantum theory. Two observations are relevant:

1. The procedure of working from theory to experiment is what minding quanta and cosmology is all about. Our brain is central to this endeavor. Rodolfo Llinás in *I of the Vortex* (2001) develops the theme that the whole purpose of having a brain is to anticipate a useful choice on the basis of past experience—the essence of a well-developed theory.
2. Brain dynamics allows conscious experiences (musings) to be momentarily superfluous to making choices; due to this delay these experiences can become esthetically elegant. Einstein's oft-quoted remark that theory must first be beautiful to be true (before its full value can be experimentally fulfilled) is a case in point.

Henry Stapp (1997) encapsulates these two observations: " . . . body/brain processes generate possibilities that correspond to possible experiences, and then [as we navigate our world] nature selects, in accordance with the basic quantum statistical rule, one of these possible experiences, and actualizes it, and its body/brain counterpart— this means that our experiences are not only the basic realities of the theory and the link to science . . . but also [that they] play a key role in specifying the 'set of allowable possibilities' that . . . [compose] mind/brain events." (Recall the correspondence between statistical, used by Stapp, and spectral representations to bring his comments into register with this essay).

# Quantum Weirdness

The conceptualizations that have characterized quantum physics for almost a century have struck scientists as bizarre and weird. When taken within the framework of "Minding Quanta" as detailed in this essay, the weirdness can be dispelled to a large extent. First, the hologram, embodying the spectral domain at the classical scale, is just as weird as is the entanglement observed at the quantum scale. (Probability amplitudes remain specific to the quantum scale but are currently under attack by Basil Hiley in an extension of David Bohm's approach to quantum phenomena.)

Second, because quantum phenomena are expressed in terms of a Hilbert space defined by both spectral and space-time coordinates, verbal interpretation often seesaws between these axes. Language has a tendency to reify, make "things" out of processes. This can be useful as in such disciplines as biochemistry when the juice squeezed out of the pituitary gland has effects on most of the other endocrine glands: The juice is assumed to be composed of a multiplicity of substances, things, each having a specific target in one of the other glands. And indeed this is what was found.

But reification can have drawbacks when the labels used to "thingify" do not properly correspond to the process being labeled. My first encounter with this issue was when we recorded a direct sensory input from the sciatic nerve to the "motor" cortex of the brain. According to the dictum of separation of input from output as in the reflex arc of the spinal cord (known as the Law of Bell and Magendie), the "motor cortex" should have no direct sensory input. I called two of the most active and respected scientists working in the field who replied, "Yes, we've seen this strange artifact over and over." But it wasn't an artifact as my students and I showed. I removed all possible indirect sensory inputs (post central cortex and cerebellar hemispheres) without disrupting the response evoked by the sciatic stimulation. The designation "motor" had misled and the reification of the Law of Bell and Magendie turned out to be erroneous even at the spinal reflex level. (The nervous system works much more like a thermostat with a control wheel to change a setting as developed in Miller, Galanter and Pribram 1960, Pribram 1971.)

When an enfolded system with space-time constraints, a Hilbert space, is being investigated, the temptation is overwhelming to reify the process in terms of the space and time constraints within which we ordinarily navigate. Take for instance the excellent book by George Greenstein and Arthur Zajonc entitled *The Quantum Challenge*. They describe what are considered to be bizarre quantum phenomena: 1) a particle can pass through two slits at the same time; 2) measurements can never be perfectly accurate but are beset by a fundamental uncertainty; and 3) the very concept of cause and effect must be rethought.

Their first chapter tackles the two-slit issue. The authors carefully describe matter waves and Louis DeBroglie's description of a quantum particle in terms of wave forms: "the quantum treatment deals primarily with waves rather than particles. Indeed the very word 'particle' plays little part in the discussion. The concept comes in only when psi is used as a measure to discern the probability of finding 'the particle' at a given point in space." As noted above, the "wave" and statistical description are to a large extent interchangeable. Here the "particle" is not a thing, not an "it" but a statistical possibility that can occur in two spatially separated slits at the same time. Equally important the "wave" in the above quotation is really not a wave which occurs in space-time but a spectral pattern created by interference among waves. David Bohm had to chastise me on several occasions before I stopped thinking of waves and began to think in terms of spectra in this context.

Greenstein and Zajonc come to the conclusion: "Clearly, if we take quantum mechanics seriously as making statements about the real world, then the demands on our conventional thinking are enormous." *At this point recall my claim that "conventional thinking" is prejudiced by lenses and the lense-like operations of our senses.* Greenstein and Zajonc continue: "Hidden behind the discrete and independent objects of the sense world is an entangled realm in which the simple notions of identity and locality no longer apply."

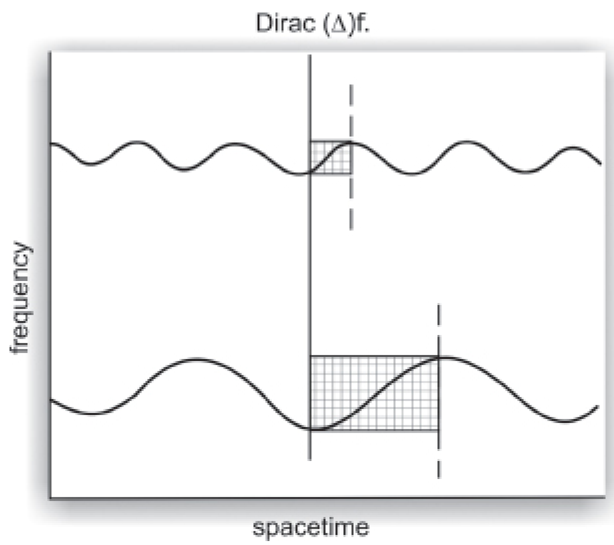
Since the early 1960s most of us have experienced in our own sense world the value of a method for attaining correlations—the Fast Fourier Transformation (FFT); and the value of the image storing and restoring powers of the holographic process. Examples of the use of "quantum holography" in image processing are tomography (PET scans and fMRI—functional Magnetic Resonance Imaging) and more recently in the operations of digital cameras.

This mathematical and engineering triumph, though available to us in the world we navigate, partakes of most of the "bizarre" attributes of quantum physics. For instance, *when space-time is Fourier transformed into the spectral domain there can be no cause and effect in the usual* *scientific sense.* The Fourier transformation is a spread function that disperses space-time events which therefore no longer exist as such. Currently scientists ordinarily seek what they call "efficient" causation in which effect follows cause. In the holographic, enfolded domain, space and time disappear, *so it is inappropriate to inquire as to where or when an efficient causal relation exists.* The transformation from space-time to spectrum (and back again to space-time) is a change in form and thus falls under Aristotle's formal causation. It is in this respect that Greenstein and Zajonc's admonition that "the very concept of cause and effect must be rethought" is honored.

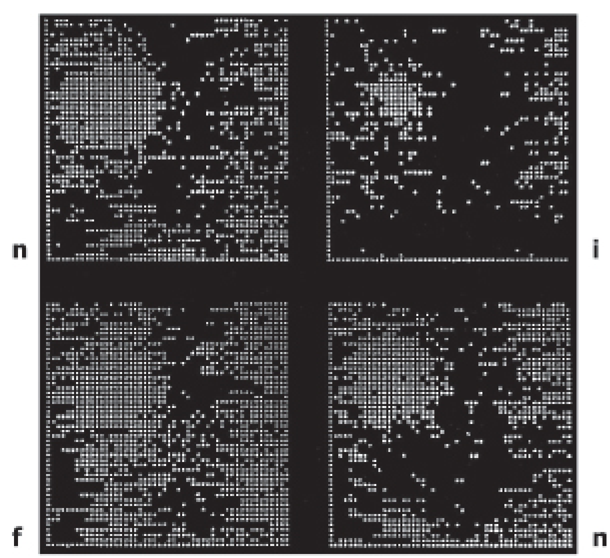
A change in form, a trans-formation in itself suggests that some uncertainty may inhere when an attempt is made to measure both spectral and space-time forms simultaneously. The world looks different when one's pupils are dilated—a sort of neutral zone between having a good pupil/ lens system and having none. A good deal of uncertainty is involved when one tries to navigate the world in this condition. Greenstein and Zajonc's second bizarre phenomenon, that measurement can never be completely accurate, actually does occur in the ordinary world of communication as well, as developed by Gabor in his (1946) "quanta of information."

An argument has been made that transformations such as the Fourier are simply conveniences to be applied as needed to describe a particular phenomenon. This is not necessarily so. The transformations describe "real world" measurements that cannot be arbitrarily assigned to one or another situation. In measuring Gabor-like (Hilbert space) processes in sensory receptive fields of the primate sensory cortex, my colleagues and I showed that electrical stimulation of the posterior part of the brain would shift the receptive field toward a space-time configuration, while stimulation of the frontal part of the brain shifted the configuration toward the spectral domain. These changes occurred in the experienced space-time world we navigate, not in an arbitrary application of mathematical whim.

In short, weirdness is not restricted to the quantum scale of observation. Instantiation of the Fourier relationship in holography has demonstrated practically identical "bizarre" characteristics. Bringing that weirdness into our everyday experience makes it less weird as we become familiar with it. Greenstein and Zajonc summarize the issue succinctly with the statement that "hidden behind the discrete and independent objects of the sense world is an entangled realm," and at the scale in which we navigate our world, is hidden a holographic universe in which are embedded the objects we perceive with our senses and actions. The enfolded realm spans all scales of inquiry from cosmic through brain processing to quantum fields and accounts for much of the weirdness encountered in attempted explanations of observations.




*102. Logons, Gabor Elementary Functions: Quanta of Information.*




*103.*

## Cosmology

I began this essay with David Bohm's observation that if we did not have telescopes and other lens-like means of observation the Universe would appear to us as a hologram. Thus the laws of optics such as the Fourier relationship are relevant to these observations. Bohm's insight implemented by the Fourier relation brings clarification not only at the quantum scale but also to cosmology. The medium that allows us to observe the cosmos is radiation. Background radiation has been given several names depending on the observed data-base upon which the name is given. Bohm, called it a "quantum potential"; Puttoff calls it "zero point energy." In conversations with each of them they agreed that the structure of this background radiation is holographic. Currently, the terms "Dark Energy" and even "Dark Matter" have surfaced as having to be measured and conceived in terms other than space and time. By analogy with potential and kinetic energy, I conceive of both these "hidden" quantum and cosmological constructs as referring to a "potential reality" which lies behind the space-time "experienced reality" within which we ordinarily navigate.

In a recent Smithsonian presentation, Roger Penrose revealed that by using his famous techniques of *conformal rescaling* he has reformulated what occurs at the horizons of our universe, both with respect to the "big bang" and its presumed ever-accelerating expansion. Instead of a big hot bang, he finds the metaphor of "a gentle rain falling upon a quiet lake, each drop making ripples that spread to intersect with other ripples made by other drops." The patterns recur at the "expanding" future boundary of the universe. These patterns are, of course, holographic. Penrose's fertile brain has made it possible for him to reformulate currently accepted dogma with an alternative more compatible with Buddhist and Hindu teachings than with the creationism of the Judeo-Christian-Islamic tradition. Important here is not whether one or another view of the cosmos is correct, but that Penrose could use an intellectual brain-formed tool, "conformal rescaling," to provide a cosmology totally different from a currently mainstream scientific conception.

I am deeply grateful to Patrick Heelan for his encouragement, interest and critique of earlier drafts.

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# Appendix B
## As Below, So Above

## The Quest

There are more than 37,000 neuroscientists currently performing experiments that address the topics that have formed my scientific life and the chapters in this book. From them we can expect a torrent of research results that bear on the health of our bodies and our brains. But there is more we need to know. I am often asked what all this research is good for? My answer is the one Faraday gave when asked this question regarding his discoveries of the properties of electricity: “Someday you’ll be able to tax it.”

My more serious answer addresses the very issue that lies at the heart of today’s quandary: As a result of the industrial revolution and modern scientific advances we have spawned a materialist society that fails to address the spiritual quest that nurtures us. I hold that using the research results I’ve reported in *The Form Within* and the interpretations I’ve derived from them, we can chart a course that reverses this strictly materialist image of ourselves.

It is time for us to consider how our scene has changed. How have the experimental achievements of the last half-century—as recounted here—altered our views? Most important, “in ancient times” we navigated our world and discovered experiences in ourselves that reflected what we observed in that world: We woke at sunrise and slept at sunset. We were intimately connected at every level with the cycles of nature. This process was disrupted by the Copernican revolution, by its aftermaths in biology—even by our explorations of quantum physics and cosmology—and in the resulting interpretations of our personal experiences. But today, once again, we have rediscovered that it is we who observe our cosmos and are aware that we observe; that it is we who observe our navigation of our world and observe our own observations.

This overturning of the balance between the priority given to observations of the world we navigate and the priority given to the navigation process itself reverses a trend that began with Copernicus and

Galileo and was continued by Darwin and Freud. The oft-lamented shift in perspective that moved the cortical human away from being the center of his universe is being reversed. But there is also a change from the earlier view: No longer is it "as above, so below;" now the cortical human is making his navigations, his quest, the means to create his world: "as below, so above."

"Remembrances-of-things-future" takes on a special flavor when we apply this concept to *Homo sapiens sapiens*. As *Sapiens*, we note that others are mortal and, by way of remembrance-of-the-future, we are able to extrapolate from such observations that we too may die. Our "Narrative I" is made up of episodes that have a beginning and an ending. Our beginning originates in our mother/mater/ matter. We can prolong our narrative by including episodes experienced with or by our biological or creative offspring and their descendants—as well as by documenting in symbols the situations in which our personal episodes have occurred. Thus by our creativity we are circumventing our ending in death.

When we humans find ourselves in situations that are difficult to navigate, we seek to "formulate" the situation, that is to create form as a basis for continuing our navigation: we create (hi)-stories or do science, or both. The quest for form can be seen as a spiritual endeavor. As such, the quest pursued by scientists is spiritual, that is, it is pursued with "a special attitude or frame of mind characterizing and animating an individual or a group" (*Webster's International Dictionary*). Many of my most creative colleagues have expressed awe and wonder at what they and others have discovered. Scientific exploration is a spiritual process in which *Homo sapiens sapiens* excels.

Spirit is ordinarily defined as being immaterial. As I recounted in Chapter 24, thermodynamics is a scientific endeavor that is based on the utilization of forms of energy, not matter. Also, descriptions of holoflux, (the quantum potential, zero-point energy) and quantum holography are devoid of any space-time structure. These endeavors are scientific and the patterns they investigate describe the patterns ordinarily probed under the rubric "spirit." There was a time when brain processes were described as mediated by "breath"—that is, spirit. Now we affirm that these "spirits" are electrical, and in the small-fibered web, they form electrical fields. And as we continue to explore the effects of magnetism and "soft photons," that is of heat, there is likely a great deal more we will discover about brain processing that affirms our spiritual nature.

We know that *Homo sapiens sapiens* has experienced the spiritual aspect of "being" since the dawn of our species. Science is a quest and, as I have tried to show, there is no reason scientists should continue to restrict that quest to be confined merely to the composition of matter.

I remember my colleagues' and my excitement some 75 years ago when, in Ralph Gerard's laboratory at the University of Chicago, we tapped a cat's paw and instantly obtained a response from an electrode implanted in the cat's brain The electrode was hooked up to a loudspeaker and every time we tapped the paw, the loudspeaker emitted a pulse. The cat's brain had registered an event that had occurred in the cat's external environment! For the first time we realized that it might be possible for us to track how environmental stimulation could be remembered.

Initially, many of us believed that the shape of the environmental stimulus would simply be "stamped" in: Plato had suggested that memory worked something like a piece of wax upon which experience becomes stamped. But as as I've explored through my research and explained in these chapters, the formation of a memory has been revealed to be much, much more complex and fascinating, far beyond the expectations any of us had when we made those first observations.

I'll recap here some of that complexity: Comprehension is enhanced by the sampling operations of the posterior sensory-specific "association" cortex. Our choices of what to sample are based on several things: in our familiarity with painful and pleasant consequences of our prior choices which are processed by our limbic basal ganglia— and in our estimate of the likelihood that a current choice will successfully yield a pleasant outcome, an estimate that involves the frontal cortex.

We can parse our experiences in many ways. In cosmology, we call this a "many worlds" solution to "what is really out there." By knowing how our senses and our brains operate, we can reduce the number of possibilities, of "worlds," that our research is still uncovering. (See Appendix A for specific details on how our speculations about the cosmos are formed by our biology and the culture we live in.)

A problem arises in the brain/behavior/mind sciences when brought to bear on our experience of right and wrong. One direct solution is to declare that doing right leads to pleasure, doing wrong leads to pain. The complexities that devolve from such a direct attempt at solution have been argued for millennia. For the brain sciences per se, the issue is not what is right and wrong, but that *Sapiens* has the ability to conceive of rightness and wrongness. Conceiving right and wrong entails consciousness and conscious choice. The word *conscience* in the French language makes no distinction between (in English) "consciousness" and "conscience."

The quest for how our brains operate to enable us to distinguish right from wrong is a fascinating one. The first steps were taken in applying the concepts of economic utility theory as I've described in Chapter 16. Later experiments have revealed to us common errors that we humans routinely make in our judgments. There is promise, as we find out more about exactly how the brain works when we are making such errors, that we can circumvent them.

Dreams, drugs and Zen meditation have in common their ability to dissolve the boundaries that ordinarily define our ability to formulate right and wrong, boundaries that we ordinarily use to navigate our world. Both in science and in the humanities, we construct such boundaries to give shape to our physical and social our worlds.

One winter morning at Stanford, I began my course in neuropsychology by pointing out that I was making an assumption fundamental to the way I was going to present the course material. The assumption was that our skin serves as a boundary between our environment and the internal workings of our body. This boundary is, to some considerable extent, a fiction: Is the boundary to be placed inside our socks or outside our shoes? Are our eyeglasses a part of the boundary? Or are they a boundary only when they are contact lenses?

Boundaries determine what is "without" and what is "within." Much has been learned about what we experience about what is "out there" in relation to what is "in here" from experiments consequent to fitting the glasses with prisms that invert the visual world—which by navigating that world it again is perceived as right-side up. The results of these experiments showed that the boundary between our egocentric (in here) and our allocentric (out there) space is placed at the end of our reach.

One morning,I described to my class these examples that raise the issue as to whether the skin can really be considered a boundary between our self and the outside world, an issue that needs to be kept in mind. But I also stated that I was positing, for the course ahead, that the skin is most conveniently conceived as a boundary.

That noon, at the Palo Alto Research Institute I heard a talk given by Alan Watts. Watts had just returned from a sojourn in Japan where he had undertaken to understand Zen Buddhism. The contents of his talk that afternoon, which would later became the topic of his famous book *Psychotherapy East and West*, was that Zen taught you that the skin is an artificial boundary! When we hold onto the boundary, we either blame our parents for our ills, or we blame ourselves. Neither is healthy. When we insist on assigning responsibility, we make us less response-able.

Whatever happens happens, and we can try to find out what multiple transactions and transformations are involved. We need not put all the burden of "guilt" on ourselves, nor pass it off onto others.

Meditative exercises, drugs and dreams go further in dissolving these boundaries. First, we experience patterns rather than shapes and, if taken to the extreme, we can experience the loss of patterns as well: only a holo-flux, "the white light" remains.

Similarly, the boundary between what we call "science" and what we call "story" is only "skin deep" and not always as clear as is generally held. During the 1960s, I used to remark that science and the scientific method provide by far the best way humans have found to share our experience of the world. The scientific method, with its constant probing and reformulating, provides one excellent means toward refreshing communication. But it is the communication that applies the skills of the humanities that makes science's stories sharable.

## The Two Cultures

The methods of science and the methods of the humanities can, to some extent, be distinguished. But is the quest that is engaged by the different methods distinguishable? *Sapiens sapiens*, the cortical primate, seeks knowledge and security. These come together in a quest for meaning.

Choosing always begets risks. The consequences of choosing can be painful or pleasurable—or, more often than not, some of both. I had the pleasure of seeing a drama in Bali that portrayed the following scenario: The hero had taken a risk and made a choice that had painful consequences for himself and his loved ones. The "devil" came and took him away—the hero died. Mourning. A funeral procession. Doleful music. About halfway through the course of the procession the motif of the music began to be uplifting—as were the middle parts of the garments covering the corpse. Before long a huge artificially rigged erection adorned the midsection of the corpse and great rejoicing came over the crowd. But that was not the end of it. A long sermon followed the uniting of the hero with his sweetheart. The sermon, accompanied by pantomime and puppetry, proclaimed that according to Balinese historical tradition "every choice we make, every action we take, has good as well as bad consequences—and furthermore, not choosing, not acting, is a choice, is an action." The hero and his bride had experienced the bad consequences and now had been given the chance to act on the good consequences of what had transpired: a lovely dramatization that embodies the wisdom of the Balinese culture.

There have been many statements made recently that science has banished mankind from the center of his universe and therefore impoverished his spirituality. This has not been my experience as a scientist—nor that of many of my colleagues. In fact as I read them, the major contributors to moving us from an egocentric view of ourselves—the scientists who have made the major contributions to the Copernican revolution, to Darwinian evolution or to Freudian psychoanalysis—never expressed any effacement of spirit or spirituality. Quite the contrary, they all were profound "thinkers," that is, doubters. Therein lies a paradox.

Without doubt, there is no belief. If there were no doubt, experiences would just be. As in the case of materialism and mentalism, the one could not be articulated without the other. If there is no up, there can be no down. Doubt engenders quest and quest engenders belief. Belief comes in a range of ambiguity, and thus offers us a range of assurance—and each of us differs in our tolerance of ambiguity. Assurance can be centered on oneself, or on the world we navigate.

During the 1960s, I sat on a variety of committees public and private, that were determining the distribution of fellowships. I tried always to see to it that the fellowships would include funds for the recipient's family so that the acceptance of the fellowship would not be disruptive. I placed great faith in the fellowship programs to further science scholarship and productivity.

A decade later, I began to realize that one could not rely on these fellowship programs. They had their own agendas. One such agenda might be to support start-up investigations. Another might be to fund research that would have a high probability of visible payoff. In view of these experiences, I began to train my students to rely on themselves, to decide what research they wanted to accomplish, and where the best laboratories were to accomplish their aims. They had to have the assurance that would develop our science in innovative directions—one could not rely on "institutions" to do this.

My experience in brain research has taken a course similar to the one that I found to characterize the science support system. As a behaviorist, I sought the formative influence on the brain and on behavior to be the shaping of more or less initially random behavior by environment. But as I have described, not only I, but the whole field of psychological science, has found that the wellsprings of behavior lie in our navigating the world we experience and that our navigations shape our brains and the environment we experience.

We, *Homo sapiens sapiens* embrace among our experiences non-material, spiritual qualities. Much of the research that I have reported here has dealt with forms, with patterns, that are, in themselves, not matter per se. These patterns can be considered the spiritual complements of matter. In this sense, spirit and spirituality now have status as topics ripe for scientific investigation.

## So Above

One of my cherished examples of the wonder that is opened up to us through scientific exploration, is the knowledge revealed in the action of chlorophyll. We have all admired Einstein's formulation of the relation between energy and matter in the equation $E = mc^2$. But chlorophyll actually performs Eintein's equation by transforming radiation from the heavens to our planet into usable energy in plants that feed animals, and it has done so for ages on end. Our scientific explorations of the origins and evolution of chlorophyll, and the manner in which chlorophyll works, make for an "awesome" and "wonderful" tale indeed.

The brain is to mind what chlorophyll is to life. The brain has made possible a transformation from merely "behaving" in a rote fashion to “minding,” that is, to thinking, intending, and attending. Our brain does this by actively transforming our future from what it has collected and processed from our past experience.

Viewed from the vantage of discoveries in the brain sciences that I have surveyed in *The Form Within*, the world we navigate takes on a renewed radiance. A technical definition of “radiance” given in Webster’s dictionary is: “the flux density of radiant energy per unit solid [three-dimensional] angle”: that is, a holoflux.

The radiance we experience in a rainbow is created by interference patterns among a bounded bandwidth of wavelets. Experiencing radiance is in keeping with the Pythagorean theme we’ve become familiar with in *The Form Within,* wherein I have here recounted the story of one quest for that elusory “pot of gold” heralded by the radiance of the rainbow.

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## Z

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