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The Deep and Surface Structure of Memory and Conscious Learning: Toward a 21st-Century Model

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> *Sir Arthur Eddington, the British astronomer, once remarked that "You cannot believe in astronomical observations before they are confirmed by theory." Much the same applies to the experiments we do in biology: we can begin to believe in results only if we have an adequate grasp of the theories that seek to explain the nature of the systems we study.*
>
> —Gordon M. Shepherd (1988, p. 91)

What might theories within the brain-behavioral sciences be like a decade or two hence? Despite some considerable trepidation, I shall ruminate on two topics because of their abiding interest to me: (1) the deep and surface structure of memory and (2) conscious learning as self-organization. I will do this in terms of outlines of models based on my own experience, with the hope that these outlines provide the skeleton for current and future work that will flesh them out.

The Deep and Surface Structure of Memory

Memory loss due to brain injury ordinarily encompasses a category of processing: prosopagnosia (inability to recognize faces); tactile agnosia; aphasia (inability to speak), and so forth. But the category can be narrowly restricted—for instance, to living vs. nonliving items or unfamiliar perspectives on familiar objects. Furthermore, whenever we wish to recall something or other, we find it useful to employ a very specific trigger that provides entry into the retrieval structure. Still, specific memories (engrams) are rarely "lost" due to brain injury. This has given rise to the view that, ultimately, storage of experience in the brain is distributed. What kind of brain process can account for both the specificity of memory and distribution?

From a 21st-century vantage, I will conceive of the organization of memory storage to resemble somewhat the organization proposed by Chomsky (1965) for language: memory has a deep and a surface structure. The deep structure of memory is distributed in the connection web of brain tissue; its surface structure is encompassed in specific circuits which are dispositions toward patterned propagation of signals preformed genetically or on the basis of experience, or both. Retrieval entails a process whereby brain circuitry addresses the distributed store. Smolensky (1986) has captured the formal essence of the process that characterizes the retrieval process, the surface structure of memory: "The concept of memory retrieval is reformalized in terms of the continuous evolution of a dynamical system [embodied in the function of a circuit] towards a point attractor [a trigger] whose position in the state space [the distributed store] is the memory. You naturally get dynamics of the system so that its attractors are located where the memories are supposed to be. . . ." (pp. 194–281). In short, the process of remembering operates on a dismembered store by initiating a temporary dominant focus of excitation in the dendritic net. Smolensky's suggestion is made more plausible if the "location" of attractors is content determined, that is, if the process is essentially content addressable—by a similarity matching procedure—rather than location addressable.

In everyday life, we experience the type of process described above if we have mastered two languages. When speaking either language, we readily address the contents of our stored experience, our memories (deep structure), but we do so in a totally different manner in each language. The difference is so great that unless one is an experienced translator, one has great difficulty in shifting from one language structure to the other. But the "items" of stored experience, such as the clothes we wear, the places we work and live in, the relationships we practice, are accessible to both languages. More on this presently.

DEEP STRUCTURE

Neurons are nerve cells that are made up of a cell body, small-diameter branching extensions from the cell body (dendrites), and often another single extension (an axon), usually larger and possessing properties different from the dendrites. As axons approach the dendrites of another neuron, the axons branch and thus resemble dendrites in that their diameters are also very small.

This is an important consideration because the amplitude and speed of propagation of an electrical signal in an axon are proportional to the diameter (actually the membrane circumference) of the nerve fiber—thus, in the terminal axon branches signals become of such low amplitude that for the most part, a chemical booster has to be released to influence the postsynaptic site. Furthermore, because of the marked slowing of signals, they interact by passive spread rather than by an active propagation, as in large axonic or nerve trunks.

With guarded hope, I foresee that during the 21st century, it will become evident to everyone that the deep distributed structure of memory storage is taking place within the brain's connective web, that is, at the synaptodendritic level of processing. One of the most intractable problems facing brain neurophysiologists has been to trace the passage of signals through the dendritic trees of neurons. The received opinion is that such signals accumulate from their origins at synapses, by simple summation of excitatory and inhibitory postsynaptic potentials, to influence the cell body and its axon and thus the cell's output. This is not the case. Each synaptic site "is functionally bipolar . . . ; it both projects synapses onto and receives synapses from many other processes. . . . Hence input and output are each distributed over the entire dendritic arborization . . . where[ever] dendrodendritic interactions are important" (Selverston et al., 1976, quoted by Shepherd, 1988, p. 82). The anatomical complexity of the brain's connective web has led to the opinion summarized by Szentagothai: "The simple laws of histodynamically polarized neurons indicating the direction of flow of excitation . . . came to an end when unfamiliar types of synapses between dendrites, cell bodies and dendrites, serial synapses etc. were found in infinite variety" (Szentagothai, 1985, p. 40).

The received opinion also focuses on the transmissive nature of synapses: Thus the term "neurotransmitters" is, more often than not, ubiquitously applied to the variety of chemical molecules secreted at axon terminals when these are stimulated by the arrival of depolarizations of axon branches at the presynaptic site. This focus on transmission appears to me to be misplaced. In any signal processing device, the last thing one wants to do if unimpeded transmission is required is to physically interrupt the carrier medium. Interruption is necessary, however, if the signal is to be processed in any fashion. Interruption allows switching, amplification, and storage to name a few purposes which physical interruptions such as synapses could make possible.

At the behavioral and experiential level, these processes make possible the distinction between memory storage processes that depend on attention—

that is, on conscious experience on the one hand and automatic processing on the other (Pribram 1971). Early on it became evident that automatic behavior and awareness are often opposed—the more efficient a performance, the less aware we become. Sherrington (1911/1947) noted this antagonism in a succinct statement: "Between reflex (automatic) action and mind there seems to be actual opposition. Reflex action and mind seem almost mutually exclusive—the more reflex, the less does mind accompany it." Additionally, however, over the past decades it has been shown that automaticity holds not only for behavior but also for processes such as attention and memory. Thus, we now distinguish between automatic and controlled processing (Bolster & Pribram, 1993) in attention and between implicit and explicit memory (Schacter & Tulving, 1994).

Evidence (Pribram, 1971) indicates that automatic processing is programmed by neural circuitry mediated by nerve impulses, whereas awareness, which provides an opportunity for conscious learning, is due to delay in processing occurring in the brain's connective web. The longer the delay between the initiation in the dendritic network of postsynaptic arrival patterns and the ultimate production of axonic departure patterns, the longer the duration of awareness and the opportunity for distributed storage. This opportunity becomes constrained as skills develop.

Daniel Alkon and his colleagues showed that as the result of Pavlovian conditioning there is an unequivocal reduction in the boundary volume of the dendritic arborizations of neurons (Alkon and Rasmussen, 1988). These neurons had previously been shown to increase their synthesis of messenger ribonucleic acid (mRNA) and specific proteins under the same Pavlovian conditions. Although these experiments were carried out in molluscs, such conditioning-induced structural changes may be akin to the synapse elimination that accompanies development as the organism gains in experience.

Before such constraints become operative, signal transmission in the dendritic network is far from straightforward. As Alkon points out in a 1989 *Scientific American* article: "Many of the molecular [and structural] transformations take place in . . . dendritic trees, which receive incoming signals. The trees are amazing for their complexity as well as for their enormous surface area. A single neuron can receive from 100,000 to 200,000 signals from separate input fibers ending on its dendritic tree. Any given sensory pattern probably stimulates a relatively small percentage of sites on a tree, and so an almost endless number of patterns can be stored without saturating the system's capacity" (pp. 42–50).

The picture becomes even more complicated when we consider the spines that extend perpendicularly from the dendritic fiber—hairlike structures (cilia) onto which axon branches terminate. Each spine consists of a bulbous synaptic head and a narrow stalk which connects the head to the dendritic fiber. Thus, synaptic depolarizations and hyperpolarizations become relatively isolated from the dendritic fiber because of the high resistance to the spread of polarization posed by the narrowness of the spine stalk. It appears, therefore, "that there is an isolation of the activity at a given site from the ongoing activity in the rest of the cell.... Part of the strategy of the functional organization of a neuron is to restrict synaptic sites and action potential sites to different parts of the neuron and link them together with passive electronic spread" (Shepherd 1988, p. 137). Furthermore, "it has been shown that synaptic polarization in a spine head can spread passively with only modest decrement into a neighboring spine head" (Shepherd et al., 1985, p. 2192). The interactions among spine-originated dendritic potentials (that need to become effective at the cell's axon) thus depend on a process which is "discontinuous and resembles in this respect the saltatory conduction that takes place from node to node in myelinated nerve" (Shepherd et al. 1985, p. 2193). For details as to how this occurs, see the Appendix.

THE SURFACE STRUCTURE

With regard to the systems that encompass the brain circuitry, there is considerable agreement to the effect that at least three broad classes of memory processes can be discerned: one class encodes and decodes experiences that refer to our environment; a second class codes experienced episodes of events that relate to our interests; and a third class organizes the practice of skills. The three processes can be crudely encapsulated as encoding the what; the when and whence; and the how of experience. Within the primate forebrain, the what systems involve the distance receptor processing performed by the posterior cerebral convexity; the when and whence systems involve the frontolimbic formations; and the how systems entail the centrally located somatic motor and sensory mechanisms. It is within these systems, with their cortical and subcortical components, that the memory *circuits* necessary to retrieval become established. But the circuits composing each of the posterior, central, or frontal cortical systems can be divided into extrinsically connected (to receptors and effectors) projection systems and so-called association systems intrinsically connected in large measure to other brain and brain stem structures.

J. Z. Young (1962), over 30 years ago, developed the theme that the primary sensory projection systems of the brain have evolved to map the sensory environment, whereas the more intrinsically connected "association" cortex performs abstract computations on the mapping functions. In discussing his paper, I (Pribram, 1963) presented evidence that the abstract computations were composed by sampling the maps in a top-down fashion. More recently, a great deal of interest has been generated by Shiffrin and Schneider's (1984) observations of the conditions that predispose humans toward automatic processing as opposed to those which predispose them toward consciously controlled processing of sensory input. Automatic processing was considered to operate in parallel on maps of the input; controlled processing was considered to entail scans (searches) of the input.

Experiments by Efron have called attention to the fact that a variety of hitherto conflicting or unexplained observations—especially with regard to differences in hemispheric function—can be understood in terms of the order in which sensory input is sampled, or scanned (for a review, see Efron, 1989). Scanning was shown to occur during a postexposure period and thus to be independent of eye movement. Some central brain process—the same as that which provides the surface structure of memory?—shown to be influenced by prior experience was inferred to be responsible.

Studies were undertaken to investigate under what conditions sampling entailed scan and what extent of intrinsic cortex might be involved in sampling procedures. Tasks were modified from Treisman's (1969) "disjunctive" vs. "conjunctive" displays in keeping with Shiffrin and Schneider's (1984) procedures: the display *set*—the nature and number of distractors in an array—was manipulated. Such procedures had, in other studies (Douglas et al., 1969; Douglas & Pribram, 1969; Pribram, 1960), been shown to be sensitive to the effects of brain damage.

The results showed that when reaction times are prolonged, differences in stimulus-evoked brain electrical responses are recorded from intrinsically connected association cortex and not from projection cortex. Furthermore, such differences were obtained from *all* three locations within the intrinsic cortex from which recordings were made. This suggests that more than one single process is responsible for the increase in reaction times, and thus, for the scanning procedure necessary to the organization of the surface structure of memory: (1) location search (parietal), (2) generating a scanplan to deal with the covarying contingencies that characterize a shared feature distractor set (frontal), and (3) bias leading to attentional fluidity (not to be confused with automaticity; temporal lobe). The most enigmatic of these factors is bias: fluidity in sampling apparently depends on comprehending not only the featural factors that directly determine the outcome of a search but ancillary task parameters and prior experience, as well.

But a great deal of the memory store is apt to be located in the basal ganglia (caudate, putamen, globus pallidus, nucleus accumbens), a repository that has been neglected in memory research. The surface structure of memory, most likely, will therefore be found to involve thalamocortical-basal ganglia-thalamcortical circuitry. Shunts will occur within the basal ganglia-thalamic portions of the circuits that allow the how, when and whence, and what processes to distribute and retrieve their respective stores within one another's confines.

Thus, during retrieval, the systems continually and rapidly interact so that we know *how* to find *what* we are looking for and monitor and store *when and whence* we find it, so that the process is facilitated the next time around.

As is well known, my bias is that this process entails a stage which is produced by transforming the ordinary space-time configurations of processing into a spectral order much as processing is done in computed tomography (CT) and magnetic resonance imaging (MRI). Only by engaging in such a harmonic transformation can the rapidity of retrieval (as in playing a piano concerto; the processing necessary to making massive correlations; and the magnitude of the memory store) be accounted for (Van Heerden, 1968).

To provide a specific model as to how such a memory storage, coding, and retrieval process might work, let me paraphrase a recent letter addressed to J. McClelland and Bruce McNaughton (6 November 1995)—filled in with appropriate material referred to in the letter:

> Ever since I saw your beautiful data in Tucson, Bruce, I have been stewing on the relationship of your findings to others. As I mentioned to J., when we strychninized the hippocampus proper, we found no exit to neocortical regions, even though *they* all "fire" the hippocampus. There are, however, massive outputs to the amygdala, perirhinal cortex and the region of the

nucleus accumbens septi from the subiculum. Thus, the problem with the model that you propose, at least as it stands, is that we would need some kind of a matching process between hippocampal space-time patterns and cortical space-time patterns. There seems to be no appropriate connectivity to accomplish this. On the other hand, if the matching (convolution/correlation) takes place in the spectral (holographic) domain via the nucleus accumbens, it could be accomplished readily.

Such a model was developed by Landfield (1976) and O'Keefe, (1986). In contrast to your own, their evidence precludes a map or representation of the environment that is in any way geometrically isomorphic with the environment represented. They suggest that the representation is of a holographic nature. O'Keefe describes their model as follows:

> 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. Furthermore, it appears that a small cluster of neighboring pyramidal cells would map, albeit crudely, the entire environment. This observation, taken together with the ease that many experimenters have had in finding place cells with arbitrarily located electrodes in the hippocampus, 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 in which information can be stored on a holographic plate and the way environments can be represented in the hippocampus is that the same hippocampal cells can participate in the representation of several environments (O'Keefe & Conway, 1978; Kubie & Ranck, 1983). In the Kubie and Ranck study the same place cell was recorded from the hippocampus of female rats in three different environments: All of the 28 non-theta cells had a place field in at least one of the environments, and 12 had a field in all three environments. There was no systematic relationship amongst the fields of the same neurone 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 repre-

> sentation of any given environment is dependent on the activity of a reasonably large group of place neurones.
>
> The third major similarity between the holographic 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 (see Landfield, 1976). In optical holography this is done by splitting a beam of monochromatic light into two, reflecting one beam off the scene to be encoded and then interacting the two beams at the plane of the substrate. In the hippocampus something similar might be happening.... The beams are formed by the activity in the fibers projecting to the hippocampus from the medial septal nucleus (MS) and the nucleus of the diagonal band of Broca (DBB).
>
> Pioneering work by Petsche, Stumpf and their colleagues (Stumpf, 1965) showed that the function of the MS and DBB nuclei was to translate the amount of activity ascending from various brainstem nuclei into a frequency moduled code. Neurons in the MS/DBB complex fire in bursts, with a burst frequency which varies from 4–12 Hz. Increases in the strength of brainstem stimulation produce increases in the frequency of the bursts but not necessarily in the number of spikes within each burst (Petsche, Gogolak and van Zweiten, 1965). It is now widely accepted that this bursting activity in the MS/DBB is responsible for the synchronization of the hippocampal theta rhythm (O'Keefe, 1986, pp. 82–84).

Let me quote from the November 1995 issue of *Scientific American* as to how such a holographic matching process could work. Of course, in this quotation, the matching process works by way of illuminating crystals, and one would have to develop neural substitutes for this (which our laboratory is currently engaged in with respect to somatosensory cortex):

> Given a hologram, either one of the two beams that interfered to create it can be used to reconstruct the other. What this means, in a holographic memory, is that it is possible not only to orient a reference beam into the crystal at a certain angle to select an individual holographic page but also to accomplish the reverse, *illuminating a crystal with one of the stored images gives rise to an approximation of the associated reference beam, reproduced as a plane wave emanating from the crystal at the appropriate angle.*

> A lens can focus this wave to a small spot whose lateral position is determined by the angle and therefore reveals the identity of the input image. If the crystal is illuminated with a hologram that is not among the stored patterns, *multiple reference beams—and therefore multiple focused spots, are the result. The brightness of each spot is proportional to the degree of similarity between the input image and each of the stored patterns.* In other words, *the array of spots [weights in a layer of a PDP network] is an encoding of the input image, in terms of its similarity with the stored database of images.*
> (Psaltis & Mok, 1995, p. 76.)

Putting this together with the McClelland-McNaughton model, which is based on data which do show a representation of the *path* taken by an animal down an alley maze, it occurred to me that encoding in the hippocampus may be both holographic-like *and* patterned in space and time. The hypothesis would be that the transformation from the spectral domain into space-time coordinates is due to a selected movement, to taking a particular path at a particular time. Thus when records are computed according to a chosen arm of the maze, a space-time representation was obtained. When records are computed as to what any cell might do over an extent of trials, a distributed holographic-like representation is found.

As noted, the shift of coordinates is suggested to take place by way of choosing a particular path. Computational models such as those proposed by Harth, Unnikrishnan and Pandya (1987) and by Yasue, Jibu and Pribram (1991) have been developed for vision to account for the shift in coordinates as a result of such a choice. In the Yasue et al. proposal, Euler-Lagrange equations correspond to *paths* taken in configuration space (spacetime coordinates). The shift from the spectral to the configuration domain has been demonstrated in the visual system both at the thalamic and cortical level. Electrical stimulation of temporal or frontal lobe cortex enhances or diminishes the extent of the inhibitory surrounds and flanks of dendritic receptive fields in thalamus and cortex so that the sensory channels can either become multiplexed or fused. As the receptive fields can be described in terms of a spacetime (configuration) constraint on a sinusoid such as the Gabor elementary function, the constraint is embodied in the inhibitory surround of the field. Enhancing the surround enhances the configuration space; diminishing the surround enhances the sinusoidal (spectral domain) aspects of processing. Movement enhances contrast which in turn depends on inhibitory surrounds.

Sincerely, Karl H. Pribram

Conscious Learning as Recoding Through Self Organization

ELEMENTS OF ACQUISITION

As noted, the deep structure of memory storage that takes place in the synaptodendritic process becomes organized into a distributed memory store. This constitutes the first step in the learning process. For these changes to become effective, they must occur both presynaptically and postsynaptically if the results of learning are to become directive to further behavior (Freud, 1895; Hebb, 1949/1961). As detailed above, the processes involving synapses have been found to be much more complicated than conceived by these early theorists. Compartmentalization of activity takes place within a dendritic arborization, even within the dendrites of a single neuron. Recall that the interaction among signals that characterizes classical conditioning turns out to involve the activity in one synaptodendritic compartment where the conditional and unconditional signals come together. Iterations of the temporal association of the signal leads to local changes in enzymes and proteins that alter the amount of potassium ion flow, which in turn alters the electrical excitability of the dendritic membrane.

However, conditioning is a fairly simple form of associative learning and may provide only the very basic element of a model for the learning process we want to occur in the classroom. The surface structure becomes involved when a student comprehends what is being presented. When a student reorganizes that presentation to fit his or her needs, the iteration of processing through the cortical-basal ganglia-thalamocortical circuits must, in some fashion, establish triggers, temporary dominant foci, as aids to retrieval. In accomplishing this, what might be the role of processes intrinsic to the learned material, as compared to those controlled by extrinsic rewards? The answers to these questions are not obvious.

In monkeys who have cheek pouches to temporarily store food, I often observed that peanuts were stored in the pouch whenever a correct response was made; however, when an error occurred, a peanut was popped out of the pouch and gleefully chewed and swallowed. We often advise our friends that when things look bleak, they should go shopping to reward themselves. How does the brain operate to associate chewing a peanut with the longer-range problem-solving process and not with the immediate error just committed? A clue may come from the observation that a challenging problem that is being mastered leads to general excitement: young male monkeys often display erections in such challenging situations. And recall Kissinger's statement that a position of power leading to political success is the best-known aphrodisiac. Some sort of internal state seems to be involved which is modulated by the organizing properties of the material to be learned.

The story of just how these two factors interact can fruitfully begin with an assessment of the effects of bilateral hippocampal gyrus resections on the performance of monkeys in a discrimination reversal procedure. In this task, the hippocampectomized monkeys show normal extinction, and the slope of acquisition of the currently appropriate response does not differ from that of the control monkeys. What does occur is a long series of trials, which intervene between extinction and acquisition, during which the monkeys select cues at random. They receive a reward approximately 50% of the time, which is sufficient to keep them working (Pribram et al., 1969). There is no obvious event that pulls them out of this "period of stationarity"; quite suddenly the hippocampectomized monkeys resume the acquisition of more rewarding behavior. What goes on during the period of stationarity, and what prolongs this period for monkeys who have had their hippocampal gyrus resected?

There are currently no techniques for directly assessing what goes on during the period of stationarity. It is clear, however, that rearrangement of the association between cue and reward has occurred when reversal is finally effected and that this rearrangement must be perceived before it can be acted on. Rearranging must be processed efficiently and appears to take effort (Pribram & McGuinness 1975, 1992; Pribram 1986, 1991).

REINFORCEMENT—A REDEFINITION

On the basis of this and other neurobehavioral investigations, some neglected aspects of the response-reinforcement relationship can be evaluated. During the heyday of stimulus-response psychology, reinforcing events were considered to be either drive inducing or drive reducing. This view foundered on neurobehavioral demonstrations that after lesions of the ventromedial hypothalamus, a rat would become obese if given food ad libitum but would starve if it had to overcome an obstacle or press a panel in order to obtain a reward (for review, see Pribram, 1970). How could a rat have both increased and decreased drive depending on the situation? How could reward be both drive inducing and drive reducing depending on the situation? The cognitive construct *effort* came closer to describing the results of the experiment than did the stimulus-response construct *drive.*

What then might effort be? Under what circumstances would effort be expended? What is the relationship between effort and reinforcement? In a seminal study, David Premack (1965) provided the first steps toward an answer to this question. Premack showed that reinforcement occurs whenever a response with a lower independent rate coincides, coheres, with stimuli that govern the occurrence of a response with a higher independent rate. Thus, the organism tends to increase the response of the lower rate to approach the rate of the response of the higher independent rate. The organism expends effort. Premack used running in an activity wheel and licking a drinking tube to measure behavioral rates of response, and showed that the reinforcing relationship was reversible depending on deprivation circumstances.

This conclusion was confirmed and enhanced by the results of an experiment performed by Herrnstein and Loveland (1975), who found that the crucial variable in reward sequences is not the probability that a response will be rewarded but rather the amount of food that appears at a given location in the environment per unit time (see Gallistel, 1990, for a thorough review).

The point of these observations is that it is the consequences of behavior that stand in relation to one another, not the behaviors per se. Premack's manipulations dealt with consequential behaviors, not just any behaviors. To be consequential, the behavior must be relevant to the organism.

To be relevant (from the Latin *relevare,* to lift up), a consequence must stand out in a situation to which the organism has become habituated, a familiar situation. Relevance depends on one or more of several factors:

1. Uncompleted behavioral sequences initiated by physiological drive stimuli, such as those that produce hunger and thirst

2. Uncompleted behavioral sequences initiated by the behavioral acts themselves, such as writing a letter and finding a box to mail it (Zeigarnick, 1972)
3. Uncompleted behavioral sequences initiated by environmental contingencies, such as earthquakes or final exams

In all cases, it is the uncompleted behavioral sequences that result in relevance. And we have already noted that the behavioral response rates in Premack's experiments refer to behavioral consequences. Thus, uncompleted sequences of consequences, or more briefly the consequences per se, generate effort on the part of the organism to lift up contingencies in a situation, that is, to make them relevant.

Consequences are sequences of situations that are in some sense consonant. An organism will sense a situation to be consequential when the contingencies describing that situation covary, that is, they are consonant, coherent, with those describing prior situations. Note that it is also coherence in the conditioning situations used by Alkon, that compartmentalized changes in the synaptodendritic network occur. The experienced prior situations provide the context within which the current contingencies become relevant—that is, consequential.

In such a sequence, it is necessary to parse situations into episodes—some of which are prior to the current situation. The episode thus becomes a unit of action that is initiated and terminated by an orienting reaction. The episode provides the context within which events, defined as eventualities, consequences, occur. Events (the Latin equivalent of outcome, *ex* + *venire*) thus are the consequences of actions, for example, the consequence "8" on the throw of dice. Each throw rearranges the event structure, "relevating" a new count on the dice. The terms *outcome, event,* and *consequence* are therefore synonymous as they refer to the reinforcing process in behavioral psychology.

In short, during learning the organism tends to expend effort to reduce dissonance and enhance consonance—that is, stability—by its behavior. This is accomplished by producing environmental contingencies that covary—that is, are consonant with those that have, on prior occasions, provided temporary stabilities. In the terminology of nonlinear dynamics (chaos theory), such contingencies serve as attractors for subsequent behavior. Appropriate here is Smolensky's description (1986) of memory retrieval, which is also relevant to the storage of the surface structure of memory: "The concept of memory retrieval is reformalized in terms of the continuous evolution of a dynamical system [embodied in the function of a circuit] towards a point attractor [a trigger] whose position in the state space [the distributed store] is the memory. You naturally get dynamics of the system so that its attractors are located where the memories are supposed to be...." (pp. 194–281). But the relationship between the reinforcing process, event structures, and deterministic chaos is a story of which the details need still to be worked out and thus are left for another day.

Meanwhile, the enigma of reinforcement is gradually yielding its secrets. The question is: What is the nature of the stored representation of prior reinforcing environmental contingencies that makes it possible for an organism to select current environmental contingencies consonant with such a representation?

The direction that can be taken by research into the process by which the environmental contingencies can be represented has been explored in detail for timing behavior. Killeen and Fetterman (1988) and Killeen (1994) presented a comprehensive review of the literature and a computational model of timing (as well as generalization and discrimination) based on their own research with rats and pigeons. The model consists of an internal, biological clock and an environmentally driven counter or accumulator. The pacemaker is based on a neural oscillator, probably of the relaxation type, which generates pulses. The process is described by a quantal model akin to that which produces Gabor functions for the visual system (Pribram & Carlton, 1986). The counter accumulates these pulses and creates a signal when the accumulation equals or exceeds some present value. The signal defines the animal's transit from one behavioral state to the next: that is, in the terminology used in the current chapter, the transit from one episode to the next.

The pacemaker is affected by a variety of biological variables such as drugs (Pöppel, 1972), temperature (Hoagland, 1935), and time of day. In addition, timing behavior is influenced by arousal (Treisman, 1969). Killeen et al., (1978) then showed that arousal is directly proportional to the rate of reinforcement and thus a function of the accumulator in the model. We are, therefore, returned to the argument, based on Premack's data, that the density of environmental outcomes of behavior is the critical variable in determining future behavior. In the model presented by Killeen and Fetterman (1988) the rate of reinforcement is reflected in the interresponse interval plotted as the mean density of a Poisson process. According to the data presented here, the pacemaker would most likely be diencephalic (hypothalamic), the amygdala system would signal change of state (episode), and the striatum (basal ganglia) would act as accumulator (see Pribram & McGuinness, 1975, 1992, for this aspect of the brain-behavior relationship). An event (computed by the hippocampal system) would perhaps correspond to the reciprocal of the mean density of the Poisson distribution of interresponse intervals. Then the process described in the letter to McClelland and McNaughton takes over.

The Big Picture: What The Relation Between the Organization of Learning and Memory and That of the Brain Can Tell Us About the Mind-Brain Connection

Often the future is a return to views expressed in the past but with new insights based on technical innovation and experimental results. With regard to science in the 21st century, we may well see a turn of the wheel toward a world view which has been submerged during the past three centuries during which attention has been focused on the composition and workings of material things. For the cognitive and neurosciences, this submergence has resulted in the received opinion that psychological processes such as learning and memory are essentially the emergent properties of brain function. The alternative view holds that, though brain is critical, brain processes reflect, in a nontrivial form, more universal orderings.

At least since the time of Newton and Leibnitz, these two rather different conceptual schemes have dominated scientific thinking: one emphasizes the lawful relation between observed events (Newton); the other emphasizes the observational medium within which observations occur. This difference in emphasis leads Newtonians to stress forces relating particles (entities) while Leibnitzians stress fluctuations (changes) composing fields. In the Leibnitzian view, entities, such as human organisms, partake of these changing fields.

The following statements place the Leibnitzian view into succinct apposition with the currently received view held by most neuroscientists:

1. The received view: Brain, by organizing the input from the physical and social environment as obtained through the senses, constructs mental phenomena.
2. The Leibnitzian view: Mental phenomena are Platonic ideals, pervasive organizing principles of the universe, which includes the brain.

Paradoxically, while almost all behavioral, cognitive, and neuroscientists would today subscribe to some form of statement 1, statement 2 reflects the belief of many influential theoretical physicists such as Dirac (1930, 1951), Einstein (1961), Heisenberg (1969), Schrödinger (1944), and Wigner (1939). Mathematicians and mathematical physicists have faced the dilemma more directly: How is it that the inventions of their brains so often describe faithfully basic orders in the universe which it then takes physicists many decades to discover?

To anticipate my own resolution to the dilemma: Dirac (1930) pointed out that a basic complementarity in physics is given by the Fourier transform. On one side of the equation are the space-time coordinates within which mass and entropy are described. On the other side of the equation are energy and momentum (measured in terms of frequency and Plank's constant). Feynman et al. (1963) note that this equation is perhaps the most fundamental in physics, and Gabor (1946, 1948) takes off from it to construct both holography and "quanta" of information. I believe that those whose conceptualizations operate primarily in space-time find the emergentist view of mind most compatible, while those who are sensitive to the energy-momentum domain are comfortable with the Leibnitzian view.

MATHEMATICAL HOLOGRAPHY IN BRAIN FUNCTION AND COSMOLOGY

The story from my perspective begins with my interactions with Dennis Gabor. In the late 1940s Gabor suggested that the resolution of electron microscopy could be enhanced if, instead of storing images directly, the photographic film would be exposed to the wave patterns of light diffracted (filtered through or reflected from) by the tissue to be examined. Gabor's suggestion was formulated mathematically. Only many years later in the early 1960s was his suggestion realized in hardware. These hardware realizations made it obvious that images of the objects that had initially diffracted the light could readily be reconstructed. Furthermore, Gabor's equations showed that the identical mathematical transfer function (the Fourier transform) transformed image into wave storage and wave storage into image! The storage of interference patterns is thus reciprocally related to the imaging of objects!!

Gabor named the stored interference pattern a hologram, because one of its most interesting characteristics is that information from the object becomes distributed over the whole photographic film. Each point of light diffracted from the object becomes blurred and is spread over the entire surface of the film (the equations that describe this are called spread functions). The spread is not haphazard, however, as the resultant blur would lead one to believe. Rather, ripples become distributed from the point of light somewhat as ripples of waves are formed when a pebble strikes the smooth surface of a pond of water. Throw a handful of pebbles into the pond, and the ripples produced by each pebble will crisscross with those produced by the other pebbles. setting up patterns of interfering wave fronts. The smooth mirror-like surface has become blurred, but the blur has hidden within it an unsuspected orderly pattern. A photograph of the pond at this moment would be a hologram. The photographic hologram is such a frozen record of the nodes of interference among wave fronts.

It seemed immediately plausible that the distributed memory store, the deep structure of memory, of the brain might resemble this holographic record. I formulated a theory based on known neuroanatomy and known neurophysiology that could account for the brain's distributed memory store in holographic terms. In the decades since, many laboratories—including my own—have provided evidence that has sharpened the theory and given it a more precise fit to the known facts.

Essentially, the theory states that at one stage of processing, the sensory systems perform a series of Fourier-like transforms. Not only auditory processing but visual and somatic sensations are initially processed as interference patterns. As noted earlier, processing is accomplished within the connection web of the brain at the junctions of the fine branches of nerve cells.

Holography implies lack of boundaries—but boundaries abound in the brain. When such boundaries are imposed on the Fourier transformations, "quanta of information" are formed. Gabor (1946) described such an information process just prior to his invention of holography in an attempt to determine the maximum efficiency with which a communication could be sent across the Atlantic cable. His mathematics wee formulated in a matrix algebra identical to that used by Heisenberg to describe the microstructure of the atom. Thus he coined the term "quantum of information." As noted earlier, more recent speculations regarding processing in the connection web have suggested that something akin to quantum mechanical processing might, in fact, be operating. (See, e.g., Hameroff, 1987; Epilogue in Pribram, 1991; Penrose 1989, 1994; Hameroff & Penrose, 1995; Jibu et al., 1994, 1996.)

During the 1970s these Gabor functions, or wavelets, as they are now commonly called, were shown to precisely describe visual processing in the brain cortex. I therefore called this process "holonomic" to distinguish it from the unconstrained "holographic" process described earlier. However, the constraints, the boundaries which are due to neural inhibition, are relaxed by electrical excitation of the frontal and related limbic formations of the brain (Spinelli & Pribram, 1967; Lassonde, Ptito, & Pribram 1981). Processing under such circumstances becomes more truly holographic. (For the details of the experiments and their results see Lecture 10, Pribram, 1991.)

THE BRAIN-MIND RELATION

The import of these theoretical and laboratory results to understanding the brain-mind relation can be encapsulated as follows: Take computer programming as a metaphor. At some point in programming, there is a direct correspondence between the programming language and the operations of the hardware being addressed. In ordinary sequential processing configurations, machine language embodies this correspondence. Higher-order languages encode the information necessary to make the hardware run. When the word-processing program allows this essay to be written in English, there is no longer any similarity between the user's language and the binary (on/off) procedures of the computer hardware. This, therefore, expresses a dualism between mental language and material hardware operations.

Transposed from metaphor to the actual mind-brain connection, the language describing the operations of the neural wetware, the connection web, made up of dendrites and synapses and the electrochemical operations occurring therein seem far removed from the language used by behavioral scientists to describe psychological processes. But the distance which separates these languages is no greater than that which distinguishes word processing from machine language.

However, the mind-brain connection is different from that which characterizes the program-computer relationship. The mind-brain connection is composed of intimate reciprocal self-organizing procedures at every level of neural organization. High-level psychological processes such as those involved in cognition are therefore the result of cascades of biopsychological bootstrapping operations.

If we take seriously the possibility that at the level of the connection web something is occurring that is akin to a computer being programmed in machine language, the Gabor or some similar function fulfills the requirements. This function was devised to operate not only on the material level of the Atlantic cable but also to determine comprehensible telephone communication, the aim of which is mutual minding.

I propose, therefore, that at the level of processing in the connection web, a *structural* identity (such as the identify between machine language based on a binary code and the operations of computer hardware based on on/off switches) is an accurate and productive philosophical approach that describes this process. Identity becomes "isonomic" when the levels of programming languages which maintain access to the same information are taken as a metaphor for higher-level processes. But the actual procedures are instantiations (as programs) of the process, not just linguistic descriptions (Pribram 1970, 1971). *Isonomy* is defined as obeying a set of laws that are related to one another by a change in coordinates. Isonomy is akin to an identity position but takes account of levels of instantiation and thus avoids the problem of category errors such as those entailed in the liar's paradox (I am a liar). Furthermore, isonomy is framed in terms of algebraic rather than geometric homomorphisms. The procedures involved bind together the various scales of operation by way of reciprocal processes that lead to self-organizing structures. At the same time, because of their *mathematical* structure defining information-processing procedures, isonomy avoids the pitfalls of a promissory materialism and, as well, those of an evanescent unspecifiable mentalistic process.

Conclusion

There is thus good evidence that a class of orders lies behind the classical level of organization we ordinarily perceive and which can be described in Euclidean and Newtonian terms and mapped in Cartesian space-time coordinates (see also Clarke, 1995). This other class of orders is constituted of distributed organizations described as potential because of their impalpability until radical changes in appearance are realized in the transformational process. When a potential is realized, information (the form within) becomes unfolded into its ordinary space-time appearance; in the other direction, the transformation enfolds and distributes the information as this is done by the holographic process. Because work is involved in transforming, descriptions in terms of energy are suitable, and as the structure of information is what is transformed, descriptions in terms of entropy (and negentropy) are also suitable. Thus, on the one hand, there are enfolded potential orders; on the other, there are unfolded orders manifested in space-time.

Dualism of mental vs. material holds only for the ordinary world of appearances—the world described in Euclidean geometry and Newtonian mechanics. I gave an explanation of dualism (Pribram, 1965) in terms of procedural difference in approaching the hierarchy of systems that can be discerned in this world of appearances. This explanation was developed into an identity theory, a constructional realism. But it was also stated that certain questions raised by a more classical dualistic position were left unanswered by the explanations given in terms of an identity position.

Two issues can be discerned: (1) What is it that remains identical in the various levels of the hierarchy of programs or compositions? and (2) Is the correspondence between machine language (program or, see below, musical notation) and the machine or instrument's operation an identity or a duality? I believe the answer to both questions hinges on whether one concentrates on the order (form, organization) or the embodiments in which these orders become instantiated (Pribram, 1996).

There is a difference between surface structures which become transformed and the deeper isonomy which in-forms the transformations (Pribram, 1996). In brain processing, this is a difference between what transpires in the connection web and what is handled by the level of neural circuitry. In psychology, it is the difference between experiencing and behaving. Transformations are necessary to material and mental "instantiations"—Plato's particular appearances—of the ideal in-forms: the instantiation of Beethoven's Ninth Symphony is transformed from composition (a mental operation), to score (a material embodiment), to performance (more mental than material), to recording on compact disc (more material than mental), to the sensory and brain processes (material) that make for appreciative listening (mental). But the symphony as symphony remains recognizably "identical" to Beethoven's creative composition over the centuries of performances, recordings, and listenings.

Instantiations depend on transformations among orders. What remains invariant across all instantiations is "in-formation," the form within. As noted, the measure of information in Gabor's terms applies both to the organization of the material wetware of the brain and the cable hardware in telecommunication on the one hand, and on the other hand, to the organization of the mindful communication itself. Thus the "in-formation" is neutral to the material/mental dichotomy. Surprisingly, according to this analysis, it is a Platonic "idealism" that motivates the information revolution (e.g., "information-processing" approaches in cognitive science) and distinguishes it from the materialism of the industrial revolution. Further, according to my perspective, as in-formation is neither material nor mental, a scientific pragmatism akin to that practiced by Pythagoreans will displace mentalism and dualism as well as materialism as central philosophical concerns.

Thus, by temperament, I need to be grounded in the nitty-gritty of experimental and observational results as much as I am moved by the beauty of theoretical formulations expressed mathematically. Therefore, in my opinion, in the 21st century the tension between idealism (the potential), and realism (the appearance) which characterized the dialogue between Plato and Aristotle, will replace that between mentalism and materialism, a tension which, at its most productive, will lead to new directions in experimentation, observation, and mathematical theory construction in the spirit of a Pythagorean pragmaticism.

These considerations suggest that these new directions in experimentation will change the venue of science. Currently our emphasis is on what Aristotle called efficient causes, the "this causes that." According to the proposals presented in this chapter, 21st-century science will supplement searches guided by efficient causation with research guided by Aristotle's final causes. Searches guided by final causation ask how things and events are put together to be what they are and what they tend to become. This type of research, which is by no means new (especially in thermodynamics and psychophysics), emphasizes transfer functions, transformations that occur as we search for ways to understand relations among patterns at different scales of observation. The finding that atomic numbers "explain" the periodic table of elements is an example of research guided by this kind of causality.

Pythagoras examined by experiment and mathematical (thoughtful) description orders at all scales of observations available to him. These scales ranged from universal (spiritual) to those composing musical tones produced by vibrating material objects. There is every evidence, from what has occurred in the second half of the 20th century, that in the coming millennium a similar range of experience will be the grist of our explorations. At the very center of such endeavors is humankind's understanding of its relation to the universe—and at the center of this understanding lies the relation between the orders invented or discovered by the operations of that "three-pound universe," the brain, and those in which it is embedded.

As of now, these are speculative but historically well-grounded proposals that are set forth to provoke 21st-century dialogue, research, and theorizing. Anyone interested?

Appendix

The intracellular spread of dendritic polarizations can be accounted for by microtubular structures that act as wave guides and provide additional surface upon which the polarizations can act (Hagen et al., 1994; Hameroff, 1987; Penrose, 1994). The extracellular spread may be aided by a similar process taking place in the glia which show a tremendous increase in the metabolism of RNA when excited by the neurons which they envelope. But these mechanisms, by themselves, do not account for the initial relative isolation of the spine head polarizations, nor the related saltatory aspects of the process.

To account for these properties we turn to the dendritic membrane and its immediate surround. Dendritic membranes are composed of two oppositely oriented phospholipid molecules. The interior of the membrane is hydrophobic, as it is formed by "lipids which form a fluid matrix within which protein molecules are embedded—the lipids can move laterally at rates of 2 μm/sec; protein molecules move about 40 times more slowly (50 nm/sec or 3 μm/min)" (Shepherd, 1988, p. 44). Some of the intrinsic membrane proteins provide channels for ion movement across the membrane.

The outer layer of the membrane "fairly bristles with carbohydrate molecules attached to the membrane protein molecules: glycoproteins. The carbohydrate may constitute 95 percent of these molecules [which form a] long-branching structure [that resembles] a long test tube brush, or a centipede wiggling its way through the extracellular space. It attracts water, imparting a spongy torpor to the extracellular space" (Shepherd, 1988, pp. 45–46).

On the basis of these considerations, Jibu, Yasue, and I (1994, 1996) propose that a perimembranous process occurs within dendritic compartments during which boson condensation produces a dynamically ordered state in water. We have gone on to speculate that each pattern of signals exciting the dendritic arborization produces a macroscopic, ionically produced change of the charge distribution in the dendritic network, altering the water molecular field in the immediately adjacent perimembranous region. A macroscopic domain of the dynamically ordered structure of water is created in which the electric dipole density is aligned in one and the same direction. It is this domain of dynamically ordered water that is postulated to provide the extracellular perimembranous substrate of the interactions among polarizations occurring in dendritic spine heads.

The transformation of the distributed saltatory dendritic process into storage depends on the existence of "impurity," that is, ions in the dynamically ordered structure of water in the perimembranous region. Among several kinds of ions typical for the extracellular and intracellular fluid are Na^+, K^+, Ca^{2+}, Cl^-, etc. The effect of the presence of such ions in the dynamically ordered structure of water is due to the electromagnetic interaction of the coulomb type, and so its strength depends highly on the distance between each water molecule and the ion in question. Thus, patches of dendritic membrane become the site of memory storage. According to Alkon (1989), the interaction is communicated intracellularly (dromically) to the cell body which, in turn, generates factors that return (antidromically) to the site of the interaction and hard-wire it. The intracellular processes are triggered by a reduction in K^+ ion flow (which results only when the conditional and unconditional stimuli are paired).

Both the extracellular and the intracellular processes need a physical substrate, a medium, within which to accomplish the molecular transformations that lead to reduction of K^+ ion flow that accompanies conditioning. The extracellular spongy torpor produced by glycoproteins provides the necessary structure for holding perimembranous-ordered water to which ions can adhere. Internally, the dynamically ordered water can provide the substrate for dromic and antidromic conductivity in the dendritic compartment activated by the temporal association of a conditional with an unconditional input signal. The deep structure of memory storage can thus become implemented.

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