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STATUS REPORT: QUANTUM HOLOGRAPHY AND THE BRAIN

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Abstract

In 1951, reviewing the state of our knowledge of auditory processes for Steven's Handbook of Experimental Psychology, Licklider ended with: "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 (cf. Gabor 1946) of even greater generality and flexibility, one that would reduce under certain idealizing 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 to suggest that we may find the solution [to the problem of sensory processing] in quantum mechanics." (p. 993)

During the 1970s it became apparent that Gabor's notation also applied to the cerebral cortical aspect of visual and somatic sensory processing. The most elegant work was done with regards to the visual system. A recent review by Tai Sing Lee (1996) in the IEEE casts these advances in terms of 2D Gabor wavelets and indicates the importance of frames and specifies them for different sampling schemes. For the monkey, the physiological evidence indicates that the

sampling density of the visual cortical receptive fields for orientation and frequency provides an almost tight frame representation through over sampling.

Evidence from my laboratory indicates that the Gabor wavelet as recorded from the visual cortex will reduce to the spectrum and to the wave form under certain idealized conditions: electrical stimulation of the temporal lobe and frontal lobe cortices and the related basal ganglia.

The 2D Gabor function achieves the resolution limit only in its complex form. Pollen and Ronner did find quadrature phase (even-symmetric cosine and odd-symmetric sine) pairs of visual receptive fields. However, to my knowledge, this is the only such report. In large part this is due to the lack of available techniques that has existed up to now. Currently, recordings made with multiple microelectrodes and data analysis with sufficiently powerful computers has remedied this situation, and I hope to have some preliminary data to report on the conditions under which phase encoding might occur.

Another issue concerns the linearity of the sensory process. Suggestions have been made that the process is fractal rather than strictly linear. It may be that under some conditions non-linearity occurs. How pervasive are these conditions?

The neurophysiological community has come to terms with the distributed nature of what I have called the "deep structure" of cortical processing. The accepted view is that distribution entails the necessity of binding together the disparate sites of processing. Binding is accomplished by temporal synchronization, and the emphasis has been that under the conditions which produce binding, no phase lead or lag is present. If, as I believe the evidence shows, the elements of the features of an image are already conjoined in a haphazard fashion in the receptive fields of sensory cortical cells, the issue of binding disappears. Instead, an active filter, a frame, acts to "capture" the relevant feature or combination of features. Capture can be implemented by the interference effects among wavelets. Should this be shown to be correct, Gabor's prediction that we might find the solution to sensory (image) processing in the formalism (and perhaps even in the neural implementation).

Keywords

Connection Web, Dendritic Tree, Holonomic, Interference Patterns, Neural Networks, Parallel Processing, Phase Relationships, Quantum Holography, Self Organization, Receptive Fields, Wavelets

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 a principle basis for understanding hearing ever 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 & DeValois 1988 p. 3)

Why Is Quantum Holography Relevant to Brain Function?

Quantum holography, or holonomy, as applied to brain function, has several roots. Historically it developed from Lashley's (1942) concern that the specific connectivities of the nervous system cannot account for the observation that "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" (p. 306). Lashley drew on suggestions by Loeb (1907) and Goldscheider (1906), that the configurations experienced in perception might derive from excitation in the brain resembling the "force lines" that determine form during embryogenesis. Goldscheider suggested that similar lines of force are developed when sensory input excites the brain. Lashley noted that such lines of force would form interference patterns in cortical tissue. However Lashley remained perplexed regarding the neurophysiological origins of these interference patterns and how they might generate the configurations of the experiences and behavior under consideration.

The limitations of understanding the interference pattern model began to yield to further inquiry with the advent of optical holography. This invention made it

possible to specify how interference patterns could account for image (re)construction and for the distributed nature of the memory store (Van Heerden 1963; Julez & Pennington 1965; Pribram 1966; 1971; 1975). A holographic hypothesis of brain function in perception was developed into a precise computational model of brain function on the basis of the mathematics that had made holography possible (see e.g., "The Cortex as Interferometer" by Barrett 1969; "The Holographic Hypothesis of Brain Function in Perception and Memory" by Pribram, Nuwer, & Baron 1974). The computational promise and firm neurophysiological base of this model was perceived by many scientists as a starting point for what has become the "connectionist" parallel-distributed processing approach to modelling brain function in perception and learning (e.g., Anderson & Hinton; Willshaw; both in Hinton & Anderson 1981). Van Heerden noted, however, that:

Two of the most striking capabilities of human memory, however, are not present in a network. The first is our ability to recognize a person we know, when he appears in our field of view, which may contain a hundred more people. The sudden flash of recognition we may feel, this absolute certainty of "this is him and it can be nobody else", is not just a subjective emotion, but is apparently evoked only by an extremely reliable and fast form of information processing in our brain. This function of recognizing is also performed by the two-dimensional hologram, as the appearance of a bright light point in the image plane of the optical arrangement, and the brightness and sharpness of the light point are a scientific measure of the degree of recognition.

The second capability is our ability, after recognizing a person, to recall quickly a considerable amount of the information we have about this person. In an optical arrangement, the recognition signal given by the two-dimensional hologram provides the instruction for generating total recall of the relevant information from a three-dimensional hologram . . .

In information theory, recognizing, or speaking of the quantitative degree of two things being alike, is described by the correlation function of two time functions, or two images. The elaborate

computation of the correlation function can be described mathematically as a filtering operation, but the computation of the matched filter required for this filtering operation is of course as involved as the original computation. The fact that the hologram performs this filtering function with 50 per cent efficiency, and that a neurone network with simple postulated properties can do the same, is due to the fact that accidentally and fortunately - or maybe it is in the nature of things - a propagating wave field carries out automatically this laborious computation demanded by the theory.

P. J. van Heerden

Despite this acknowledgment of promise, objections, some more precisely stated than others, were raised regarding the holographic model. Certain initial objections were based on an incorrect analogy between the paraphernalia of early optical information processing techniques (such as coherent reference beams) though these were shown very early on to be unnecessary (Leith 1976; Pribram, Nuwer & Baron 1974). Other objections derived from a misidentification of the "waves" involved in holography as somehow representative of the brain waves recorded from the scalp. Macroscopic waves cannot possibly carry the amount of information necessary to account for the processing requirements involved in perception. On the other hand, spatial interactions among junctional microprocesses occurring in dendritic networks can provide the basis for extremely complex processing (Pribram 1971, chap. 8).

A more germane objection came from the fact that the mathematics involved in holography as developed by Gabor (1948), centered on the Fourier theorem. In psychophysics, therefore, it was sometimes held that the transfer function computed by the sensory system was a global Fourier transform, thus spreading the input over large extents of cortex. This was shown to be an untenable position for psychophysics (Caelli & Julesz 1979). However, the neurophysiologists who had initially formulated the hypothesis with regard to brain function had always noted that the transfer functions involved are limited to particular receptive fields -- that is, to patches of dendrites -- and that more complex relations determine processing of ensembles of such fields (Pollen 1974; Pollen, Lee, & Taylor 1971; Pribram 1966; Pribram,

Nuwer, & Baron 1974; Robson 1975; DeValois & DeValois 1988, Chapter 8).

A more fundamental difficulty for understanding had to do with the nature of the Fourier relation itself. The Fourier theorem holds that any pattern can be analyzed into a set of regular, periodic oscillations differing only in frequency, amplitude, and phase. The Fourier transform of such a pattern is described as a spectrum composed of coefficients representing the amplitudes of the intersection (quadrature) of sine and cosine components of the various frequencies present in the pattern. The medium of optical holography, the silver grains of the photographic film, encodes these coefficients. The effects of reinforcement and occlusion at the intersections among wave fronts are encoded, not the wave fronts themselves. The sites of intersection form nodes of varying amplitude, which are represented numerically by Fourier coefficients. A rainbow displays a spectrum of colors diffracted by discrete drops of moisture - the wave forms that compose the display are not seen as such. Thus, the holographic model of brain function, had to be described in the discrete terms of a complex spectral representation. Often description was erroneously made solely in terms of wave forms per se; sometimes, because of its counterintuitive nature, the spectral representation was discounted.

Holographic theory is based solely on the "either-or" Fourier duality between space-time and spectrum. The holonomic brain theory incorporates this duality but is additionally based on the delineation by Gabor of a "phase space" in which the complex of space-time and spectrum become embedded. In such a phase space, space time considerations constrain an essentially spectral computation.

The formal, mathematical foundations of the computations contributing to the holonomic brain theory rest on two fundamental concepts and the relations between them. The first basic conception is a generalization in perceptual processing of the concept of a spectral domain: Not only colors and tones can be analyzed into component frequencies. Processing of all exteroceptive sensations including those dependent on spatiotemporal configurations (such as the shapes and forms of surfaces and forms) can be understood as space time modulations of basic frequencies.

This generalization derives from plotting spectral and space time values within the same frame. It turns out that when this is done, there is a limit with which

both frequency and space time can be concurrently determined in any measurement. This minimum describes a fundamental indeterminacy or uncertainty similar to that described by Heisenberg in microphysics. Gabor therefore called his basis function (1946) a quantum of information. Gabor's formalism consisted of sinusoids variably constrained by space-time coordinates and differs from the unit of information defined by Shannon, usually taken as a bit (a binary digit), a Boolean choice between alternatives (Shannon & Weaver 1949). However, Shannon also defined information as a reduction of uncertainty. This uncertainty relationship provides a link between Gabor's and Shannon's definitions and allows for an explicit convergence of information processing theories. Furthermore, the distinction between Gabor's and Shannon's formulations provides the basis of the distinction between the configural and the cognitive aspects of perception.

How is Brain Function Relevant to Mentation?

The majority of neural processing theories since the seminal contribution of McCulloch and Pitts (1943) have taken the axonal discharge of the neuron, the nerve impulse, as the currency of neural computation. The knowledge that the neuron has only two states "firing" or "quiet" suggested comparison with the electronic computer. In their gross structures the brain and the digital computer were thus thought to have marked similarities. As Wiener noted:

... the ultra-rapid computing machine, depending as it does on consecutive switching devices, must represent almost an ideal model of the problems arising in the nervous system. The all-or-none character of the discharge of the neurons is precisely analogous to the single choice made in determining a digit on the binary scale . . . The synapse is nothing but a mechanism for determining whether a certain combination of outputs from other selected elements will or will not act as an adequate stimulus for the discharge of the next element, and must have its precise analog in the computing machine. The problem of interpreting the nature and varieties of memory

in the animal has its parallel in the problem of constructing artificial memories for the machine.

Wiener (1961, p. 14)

However, from a fine structural standpoint the brain is considerably more complex than the digital computer, and by the 1960's it was realized by some of us that the McCulloch-Pitts theory was inadequate.¹ The branching structure of dendrites (the so-called *dendritic tree*) plays a far more important and diverse role than was initially surmised and as we shall see. Furthermore, analogue computation also plays a significant role in neural computing.

My own approach in the mid 1950's differed from that of McCulloch-Pitts and the early Wiener, by focusing on the relationship of neurophysiology and mind, and taking computer programming rather than computer hardware as its metaphor (Miller, Galanter and Pribram 1960). At some point in programming, there is a direct correspondence between the programming language and the operations of the hardware being addressed. In ordinary serial processing, machine language embodies this correspondence in an easily recognizable way. Higher order languages encode in more subtle ways the information necessary to make the hardware run in more abstract and therefore general useful languages: When a 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 of the computer hardware. This, therefore, initially appears

¹ Wiener too realized the erroneousness of his earlier estimation, witness his words in 1964 in a posthumously published paper.

It is now clear that this all-or-none character is the result of the long duration in time and the long continuance in space of nervous conduction under essentially constant conditions. It is not to be expected then in a short fiber in which the remaking of the initial impulse has not had headway enough to assume its final shape or in which there are non-homogeneities such as incoming or outgoing branches as in the teledendron or the dendrites. Therefore the pattern of all-or-none activity, where highly suitable for the conduction of nervous activity in the white matter, is by no means so suitable for the study of the same sort of activity in the gray matter. As a matter of fact I believe there is positive evidence that the all-or-none hypothesis applied to the gray matter leads to false conclusions. (p. 401)

as an erroneously conceived irreconcilable dualism between mental language and material hardware operations. When, however, all the transformations, the recoding operations that lead from binary through hexadecimal codings, assemblers, operating systems and the like are available, the connection between the binary system and English becomes transparent.

Transposed from metaphor to the actual mind-brain connection, the operations of the cerebral cortex seem far removed in their organization, from the organization of our thoughts and of the psychological processes that we describe in observation sentences such as "I see a red apple." But the separation between these organizations is of the same range as that between computer programmed word processing and machine operations.

What is different in the mind-brain connection from that which characterizes the program-computer relationship is its massive parallel processing of self-organizing structures at every level. For instance, the optic nerve, which transmits visual information, has more than half-a-million parallel fibers. High level psychological processes such as those involved in cognition are therefore the result of cascades of parallel operations, involving two-way feedbacks, rather than, as in computers, the result of fairly fixed top-down programming operations.

These differences between classical computer and neural programming have led to new developments in parallel processing programming architectures called neural networks. Successful computations in these networks depend on highly -- often fault tolerant -- interconnected elements. The more diverse the computation, the more connections are needed. However, classically, neuroscientists have shown that neuronal pathways are sometimes relatively sparse, and always in a specifically configured fashion: This anatomical fact is ubiquitous but seems to be incompatible with the fact that psychological processes depend on patterns that can be transposed from one location in the body or its environment to another.²

² An example of the transposability of patterns is the reasonable fidelity of writing with one's left hand or left big toe in the sand -- or even one's teeth -- when one has never previously engaged the neuromuscular apparatus in this fashion. Even writing on the vertical surface of a blackboard engages the neuromuscular system in a different fashion from that which occurs when writing is accomplished on a horizontal surface.

Scale in Neural Processing

The problem becomes resolved when the computational framework of the neurosciences is broadened beyond nerve-impulse-transmission, to include the microprocessing that takes place within the brain's dendritic arborizations which provide the unconstrained high connectivity needed in computational processes. As noted, neurons are ordinarily conceived to be the building blocks, the units of organization, of the brain's cortex. However, as will be described shortly, this emphasis on the neuron must be supplemented by additional configurations which operate to some considerable extent as a distributed processing space independent of the neuron. The role of each neuron is to locally sample this space.

Anatomically, neurons are composed of a cell body to which are attached a set of branching input fibers called dendrites (rootlets). Extending from one location of the cell body of the neuron (its axon hillock) is a chemically different sort of nerve fiber, often longer than the others, called the axon. At its terminus the axon splits into smaller branches called nerve terminals or telodendrons. There is a minute gap called a *synapse* between the far terminus of each telodendron and the dendrites or cell body of the adjacent axon on which it impinges.

Energy inputs to dendrites are exceedingly small and must, therefore, "summate" in some way to influence (modulate) the nerve impulses that are generated by the chemical processes operating at the axon hillock. The resulting modulated series of nerve impulses propagates down the length of the axon until it reaches the telodendrons of its far terminus. When the nerve impulses reach the telodendrons, they decrement due to the small diameter of these axon branches. Thus to influence the adjacent dendrite across a synapse, the electrical signal produces one or other chemical that diffuses across the synapse. This diffusion creates an electro-chemical potential difference in the dendrites of the post synaptic neuron. This potential difference in the post synaptic neuron can be excitatory, that is, depolarizing; or it can be inhibitory, that is, hyperpolarizing. There are myriads of such synapses in the brain. I refer to the activity initiated at synapses that produces depolarization and hyperpolarization in the dendrites as occurring in the brain's *connection web*.

The myriad of synapses provide the possibility for

processing as opposed to the mere transmission of signals. The term *neurotransmitters* applied to chemicals acting at synapses is, therefore, somewhat misleading. Terms such as *neuroregulator* and *neuromodulator* convey more of the meaning of what actually transpires at synapses. When signals arrive at synapses, potential differences are enhanced creating hyper- and depolarizations. These are never solitary but constitute arrival patterns. The patterns are constituted of the periodically fluctuating hyper- and depolarizations which are insufficiently large to immediately incite nerve impulse discharge. The delay entailed in the passive transmission of these patterns affords opportunity for computation.

Thus, 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 rapidly 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 a considerable oversimplification only true when a well-established input-output relationship has been established. Before such circuits have become operational a more complex set of relationships in the processing web need to be taken into account. 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, p. 82 1988). The anatomical complexity of the dendritic network has led to the opinion summarized by Szentagothai: (1985, p. 40) "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."

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 molecular processes stimulated by the arrival of an axonic depolarization at the presynaptic site. This focus is 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 to which physical interruptions such as synapses could make possible.

What then might be the use to which synapses could be put when input and output are each distributed over an extent of teledendronic and dendritic arborization? In *Languages of the Brain* (1971), I suggested that any model we make of perceptual processes must take into account both the importance of Imaging, a process that constitutes a portion of our subjective (conscious) experience, and the fact that there are influences on behavior of which we are not aware. Automatic behavior and awareness are often opposed -- the more efficient a performance, the less we aware we become. Sherrington 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 reflex the less mind accompanies it."

Evidence was then presented that indicates that automatic behavior is programmed by neural circuitry mediated by nerve impulses, whereas awareness is due to the synaptodendritic microprocess, the excitatory and inhibitory postsynaptic potentials and their effect on dendritic processing. 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.

Recent support for this proposal comes from the work of Dan Alkon (1989) and his colleagues who showed that as the result of Pavlovian conditioning there is an unequivocal reduction in the boundary volume of the dendritic arborizations of neurons. These neurons had previously been shown to increase their synthesis of mRNA (messenger ribonucleic acid) 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, and therefore, automaticity in the appropriate sites in the cortex of rats exposed to enriched environments.

The hypothesis put forward thus states that as behavioral skills are attained, there is a progressive shortening of the duration of dendritic processing that occurs between the initiation of postsynaptic arrival

patterns and the production of axonic departure patterns. This shortening is presumed due to structural changes in the dendritic network which facilitate transmission.

But, as we have seen, initially signal transmission in the dendritic network is far from straightforward. As Alkon points out in a Scientific American article (1989): "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." (42)

A major breakthrough toward understanding the momentary patterns of such sites activated by a stimulus was achieved by Kuffler (1953). He moved a spot of light in front of a paralyzed eye and recorded the locations of the spot that produced an electrical response in the axon of a retinal ganglion cell. The direction of response, inhibitory (-) or excitatory (+), at each location indicated whether the input branches (dendrites) at that location were hyperpolarizing or depolarizing. The locations revealed the topology, the extent and shape of the responding dendritic arborization of that axon's parent neuron. The resulting diagrams of hyper- and depolarization thus revealed the *receptive fields*,³ which activate the dendrites of that axon. The receptive fields of retinal ganglion cells are found to have a circular inhibitory or excitatory center surrounded by a penumbra of opposite sign.

Utilizing Kuffler's techniques of mapping, Hubel and Wiesel (1959) discovered that for cerebral cortex the circular organization of the receptive field become elongated displaying definite and various orientations. They showed that oriented lines of light stimuli rather than spot stimuli produced the best response recorded from the axons of these cortical neurons. They

³ **Receptive Field** is defined as the area in sensory space, i.e. physical space outside the body, within which an adequate stimulus causes an excitatory response of the neuron from which recordings are being made. It is often surrounded by a sensory region, called the *nonclassical receptive field*, that can modulate the central response.

therefore concluded that these cortical neurons were "*line detectors*." In keeping with the tenets of geometry where lines are made up of points, planes of lines and solids of planes, Hubel and Wiesel suggested that line detectors were composed by convergence of inputs from neurons at earlier stages of visual processing (retinal and thalamic - which acted as spot-detectors due to the circular center-surround organization of the receptive fields.) This geometric interpretation of neuronal processing led to a search for convergences of paths from "feature detectors" such as those responding to lines, culminating in "pontifical" or "grandfather" cells that embodied the response to object-forms such as faces and hands. The search was in some instances rewarded in that single neurons might respond best to a particular object form such as a hand or face (Gross 1973). However, response is never restricted to such object-forms. Such "best" responses can also occur in parallel networks made up of neuronal ensembles in which convergence is but one mode of organization.

For those using the geometric approach, spots and lines are seen as elementary features that become combined in ever more complex forms as higher levels of the neural mechanism are engaged. In the late 1960's, however, new evidence accrued (see DeValois and DeValois 1988 for review) that called into question the view that figures were composed by convergence of such features and indicated that harmonic analysis was a better representation of what occurred in the brain.

The Brain as Harmonic Analyzer

A century ago, Helmholtz proposed that sensory receptors are akin to a piano keyboard; that a spatially isomorphic relation is maintained between receptor and cortex as in the relation between keys and strings of a piano, but that each cortical "unit" responds (resonates) to a limited bandwidth of frequencies as do the strings attached to the piano's sounding board. From the operation of the total range of such units, magnificent sounds (in the case of the piano) and sights (by means of the visual system) are engendered. James Clark-Maxwell too made a statement that foreshadowed the promise that such a harmonic approach might provide

understanding to the brain/mind relationship:

It would not be devoid of interest, had we opportunity for it, to trace the analogy between these mathematical and mechanical methods of harmonic analysis and the dynamical processes which go on when a compound ray of light is analyzed into its simple vibrations by a prism, when a particular overtone is selected from a complex tune by a resonator, and when the enormously complicated sound-wave of an orchestra, or even the discordant clamors of a crowd, are interpreted into intelligible music or language by the attentive listener, armed with the harp of three thousand strings, the resonance of which, discriminates the multifold components of the waves of the aerial ocean. (J.C. Maxwell 1952, "Harmonic Analysis", *Scientific Papers*, II, pp. 797-801).

Let us turn to the new evidence that accrued in the late 1960's which lent credence to this view of the brain. In my laboratory at Stanford University, we exposed the eye to moving dots on a computer screen and studied the different configurations of responses of the dendrites of cortical neurons, much as Kuffler had done on the retina. We found regions that contained not only a single oriented line, as had been reported by Hubel and Wiesel, but oriented bands of excitatory (indicated by an increase in firing) and inhibitory (indicated by a decrease from baseline in the neuron's firing) areas. Other workers found similar patterns. In a critical report, Poffen, Lee, and Taylor (1971) interpreted their findings to indicate that the cortical neurons were behaving as Fourier analyzers rather than as line detectors. When harmonic analysis is taken as the approach, the "multiple lines" are interpreted as "strings" tuned to a limited bandwidth of frequencies. The ensemble of strings act as resonators or active filters, as in musical instruments.

Indeed in the late 1960's, Campbell and Robson (1968) initially on the basis of psychophysical and subsequently on the basis of neurophysiological experiments, developed the thesis that vision operates harmonically much as does audition, except that the visual system responds to spatial frequencies in the Fourier transform of the visual stimulus.

There are four critical reasons for preferring an

analysis by frequencies to that of line elementary features: (a) Each neuron in the visual cortex responds to several features of sensory input, and there is no evidence that the different features are uniquely represented by any single neuron, as would be required if it acted as a feature detector. For instance, changes in orientation, spatial frequency, luminance, direction and velocity of the stimulating input all can alter the output of the neuron as gauged by its axonal discharge. (b) The form of the activity of the connection web of such neurons, as gauged by their receptive field configuration, can be accounted for by considering them as spatially and temporally constrained frequency resonators. (c) These resonators provide a potentially richer panoply for the perception of texture and parallax than do feature detectors. (d) Perceptual research has clearly shown that lines (and therefore line detectors) composing contours are inadequate elements with which to account for the pattern recognition in vision. (See Pribram 1991, Lectures 2 and 3 for details.)

Harmonic analysis has also contributed to neuroscience by its explanation of our conscious experiencing of images and objects. For instance, in every-day life we become consciously aware of a three-dimensional acoustic image in stereophonic high fidelity reproduction of music. We know the sources of the sound to be the speakers, but we also know that by adjusting the *phase relationships* between acoustic waves generated by the speakers, we can move the sound away from the two sources, to in-between the speakers and in front of them. Our ears and acoustic nervous systems reconstruct the sound to be perceived in a location we know to be incapable of producing that sound.

What determines this construction of a sound image away from its physical source? Bekesey's ingenious experiments (1960; 1967) with artificial cochleas hold the answer. By lining up five vibrators on one's forearm, Bekesey was able to produce the feeling of a single spot that could be moved up or down by changing the phase of vibrations between the vibrators. When a second artificial cochlea was placed on the opposite forearm, the feeling of a spot could be made to jump from one arm to the other. After a while the spot becomes "projected" out into the region between and in front of the arms away from the receptor surface of the skin much as sound is projected from two stereophonic speakers. However, using two arms is not a necessary condition for perceiving an

image away from the receptor surface. When phase relations between stimulations to two fingers are adjusted, a spot can be projected outward from them. One feels the paper on which one is writing at the tip of one's pencil, not at the tip of the fingers holding it. Harmonic interactions among vibrations are the necessary conditions for such perceptions.

Holographic and Holonomic Processes in the Brain

Philosophically more important (than Wiener's power spectrum) is another mathematical creation of Wiener, the "coherency matrix," and this has a curious history. It was entirely ignored in optics until it was reinvented, almost simultaneously and independently, by Dennis Gabor in England in 1955, and by Hideya Gamo in Japan in 1956. (Gabor 1981, p. 490)

In 1948 Dennis Gabor made the concept of coherence the basis of a mathematical theory aimed at improving the resolution of an image in electron microscopy. Instead of forming photometric images, which record intensities but destroy phase information, the photographic film ought to record the interference patterns of the light diffracted by the tissue to be examined. Only in the early 1960's did the advent of lasers provide the strong source of coherent light by which the process could be realized. These hardware realizations made it evident that images of the objects that had initially diffracted the light could readily be reconstructed.

Gabor named the record of interference pattern a *hologram*. A holographic process is constructed of interference patterns resulting from the intersection of coherent wave fronts. As noted, it is the interference nodes that are encoded as discrete coefficients and not the wave per se that compose the formalism that describes the hologram.

Sensory systems perform a series of operations that combine to yield the Fourier transformation of the input signal impinging on the retina (Gabor 1968; Pribram 1991, p. 73). Not only auditory processing but visual and somatic (skin, muscle and visceral) sensations are initially processed in the spectral domain. As noted, processing is accomplished in a connection web at the synapses among arborizations of neurons. Some neurons have no axons and display no nerve impulses. Their function is primarily to

influence the polarizations. They are most often found in the horizontal layers of neural tissue such as the retina and cortex in which interference patterns become constructed. This accounts for our remembering discrete items after brain damage. Sensory input must, in some form, probably as changes in the conformation of biomolecules at membrane surfaces, become encoded into distributed memory traces (see Pribram 1971, Chapter 2; Pribram 1996; and Jibu, Pribram and Yasue 1996). The biomolecules would serve as a neural "holoscape" in the same way as oxidized silver grains serve the photographic hologram. A solid body of evidence has accumulated that the auditory, somatosensory-motor, and visual systems of the brain do, in fact, process input from the senses in the spectral domain. (See Pribram 1991 and DeValois and DeValois 1988 for a review of this evidence.)

However, the patterns in the connection web are bounded by the anatomy of the neuronal branches. To deal with them, it is necessary to partition the 5-dimensional (2D spatial, 1D temporal and 2D spectral) space-time frequency hyperspace into Gabor's *logons* (see Flanagan 1972 and Pribram 1991, pp. 28-32).

This is an aspect of harmonic analysis to which first Wiener and then, more thoroughly, Dennis Gabor contributed, viz. the time-frequency restraint inherent in any complex signal, an aspect which is germane to brain science. This is the restraint imposed by the inequality:

$$\int_{-\infty}^{\infty} |f(t)|^2 dt \cdot \int_{-\infty}^{\infty} |\hat{f}(\lambda)|^2 d\lambda \geq \frac{1}{4} \left[\int_{-\infty}^{\infty} |f(t)|^2 dt \cdot \int_{-\infty}^{\infty} |\hat{f}(\lambda)|^2 d\lambda \right] \quad (1)$$

that links a function f to its Fourier transform \hat{f} . In engineering circles, it is spoken of as the time-bandwidth relation.

During the 1970's these Gabor elementary functions f , for which Equation (1) becomes an equality, (or Gabor *wavelets*, as they are now commonly called), were extended into two spatial dimensions and used to simulate the visual processing in the cortex. As noted earlier, with the advent of frequency analysis in studies of figural processing pioneered by Schade (1956), Kabrisky (1966), and Campbell and Robson (1968), the term "spatial frequency" known in optics became commonplace in the visual sciences. Applying to spectral processing a term coined by Heinrich Hertz (1884/1956) to describe

dynamical systems subject to constraints. I called the process described by Gabor as *holonomic* to emphasize that spectral processing in the nervous system is constrained by the boundary conditions imposed by the brain's anatomy.

Three issues are raised by the holonomic theory: 1) Have receptive fields been shown to process input in the space-time frequency hyperspace? 2) Have receptive fields been shown to process the phase of input? 3) And finally, as noted, Gabor used the same mathematics as did Heisenberg and therefore called his elementary functions "quanta of information." However, both Gabor and I noted that his formalism does not entail processing at the Planck scale. Nor, however, does the formalism preclude this. Thus, we need to inquire what possibilities, if any, can be delineated to show that quantum level processes can occur in the brain.

The Spectral Domain

Issue No. 1. Regarding processing in the space-time frequency hyperspace, my colleagues and I carried on the following experiment:

The rat somatosensory system was chosen for convenience and because the relation between whisker stimulation and central neural pathways has been extensively studied (Armstrong-James 1995; Simons 1995). The whisker system has the putative advantage over the visual system that greater control over the spatial location of receptors can be exercised. However, as noted by Simons (1995), "... In its function the whisker field may be more similar to a continuous receptive sheet, like skin or retina, than its punctate anatomical structure might suggest." (p. 268). Also, at the cortex, there is a good deal of evidence that the classical receptive field properties are altered by extra-field stimulation (Paradisio, M.A., Kim, W., Nayak, S. (1996); Vidyasagar, T.R. & Henry, G.H. (1996).

Methods: Whiskers were stimulated by means of a set of rotating textured cylinders, each grooved with equally spaced teeth, the tooth width and grooves subtending equal angles. (The rotating cylinders were meant to mimic the drifting of gratings across the retinal receptors in vision.) Three cylinders (2cm. in diameter and 5 cm. in length) were used with grooves and teeth each measuring 30 deg., 15 deg., and 7.5 deg., respectively (corresponding to 12, 24 and 48

teeth/cylinder). These textures were approximately the same as the coarser of those used by Carvell and Simons (1990). The cylinders were rotated at 8 different speeds, varying from 22.5 deg/sec to 360 deg/sec.

The Topology of the Functional Dendritic Receptive Field: Maps were constructed of the number of bursts or spikes per 100 seconds of stimulation generated at each spectral location as determined by the spatial and temporal parameters of an input. According to our assumption of the field/spike dual, the activity above or below baseline which resulted from whisker stimulation represents a surface distribution of local field potentials. Spatial frequencies are scaled in terms of grooves per revolution, while temporal frequencies are scaled in terms of revolutions per second. Thus, the density of stimulation of a whisker (or set of whiskers) is a function of both the spacings of the cylinder grooves and the speed with which the cylinder rotates (Figures 1a and b, 2a and b and 3a and b). Because these parameters co-determine the rate at which a whisker (or set of whiskers) is flicked, an equal flick rate ought to generate an equal number of spikes or multi-unit bursts irrespective of whether the flicks are produced by the spatial (texture) or the temporal (rotation speed) stimulus. Thus, if flick rate were critical, a cylinder with 24 grooves rotating at one revolution per second should generate an equal number of spikes and the same surface distribution of local field potentials as a cylinder with 12 grooves rotating at two revolutions per second. This expectation was not fulfilled, perhaps because a change in rotation speed results in a change in acceleration of whisker deflection, which a change in the spacing of grooves does not⁴. Thus, a three-dimensional mapping of the surface distribution of dendritic local field potentials is warranted, a distribution which is, in fact, asymmetrical with respect to its spatial and temporal axes. (See Figures 1, 2, 3)

Simulation: In order to discern whether, indeed, our

⁴The burst rate during stimulation is not synchronized to whisker stimulation; for example, when actual whisker stimulation is occurring at about 3 stimulations per second, the burst rate is about 8 bursts per second. Our baselines were composites of 100 sec of pre- and 100 sec of post-stimulation recordings. In a separate study (Xie, M., Pribram, K., King, J. 1994) using the same baseline data, we showed the spike trains to be stochastic (and, in longer runs, stationary), not deterministically chaotic.

data fit the requirements of signal processing theory, a simulation of the procedure was executed. The first stage of the simulation was to construct a putative map of the surface distribution of fluctuating local field potentials in patches of cortex. In order to provide a pattern of peaks and valleys similar to that shown by our data, we chose a rectangular window in the spatiotemporal domain to constrain a two dimensional sinusoidal signal, because when the extent of the signal is pruned of noise, a rectangular region is obtained in the results of experiments recorded from visual cortical neurons (Gaska, J.P., Jacobson, L.D., Chen, H.W., and Pollen, D.A. 1994). In addition, the rectangular window allows for maximum resolution of frequencies (Zeevi, Y.Y. & Daugman, J.G. 1981; Oppenheim, A.V., and Schaffer, R.W. 1989). The use of such a window generates a sinc function in the spectral domain.

In our simulations, each plot shows the surface distribution of a spectral density function of a rectangular windowed two-dimensional sinusoidal signal. When, in other experiments, only a single frequency of stimulation is used, a spatial "connection" matrix can be constructed from recordings made with multiple electrode arrays to represent the data (Barcala, L.A., Nicoletti, M.A.L., and Chapin, J.K. 1993; Chapin, J.K., Markowitz, R.S., & Nicoletti, M.A.L. 1996; Nicoletti, M.A.L., Carswell, B., Oliveira, L.M.O., Ghazanfar, A.A., Chapin, J.K., Liu, R.C.S., Nelson, R.J., & Kaas, J.H. 1996; Ahissar, E., Alkon, G., Zacksenhouse, M., & Haidarliu, S. 1996; McLaughlin, D.F., Sonty, R.V. & Juliano, S.L. 1996). In our version of such a matrix, the surface distribution of local field potentials in a patch of cortical tissue can be conceived to act as an "ideal" filter which processes incoming signals. This ideal filter when activated generates a sinc function which is defined as:

$$\text{sinc}(\omega) = \frac{\sin(\omega)}{\omega} \quad (2)$$

for all values of the spectrum that activate the filter (Kamen 1990).

As we used two parameters of stimulation, spatial and temporal frequency, the sinc function becomes two dimensional as follows:

$$F(\omega_1, \omega_2) = A \text{sinc}(\omega_1) \text{sinc}(\omega_2) \quad (3)$$

for all values within the range of values specified for (2) above, and where ω_1 and ω_2 correspond to the representation of spatial and temporal frequency in the computational space.

In simulating our data, the sinc function must, therefore, be defined for a range of stimulus parameters within a computational space in which an incoming signal is processed. Each signal generates a sinc function within that space, the peak of which will be located at some given temporal and spatial value. Therefore, the actual sinc function generated by each two-dimensional signal will be displaced from the origin of the computational space by the difference between the spectral frequencies which define the computational space and the actual frequencies generated by the incoming signal. The sinc function produced by the incoming signal will thus be defined by:

$$F(\omega_1, \omega_2) = A \text{sinc}(\omega_1 - \omega_{01}) \text{sinc}(\omega_2 - \omega_{02}) \quad (4)$$

where A is a scaling constant, ω_1 and ω_2 are spatial and temporal frequencies of the computational space, and ω_{01} and ω_{02} are the spatial and temporal frequencies of the signal.

Systematically changing the parameters of stimulation, therefore, serves to systematically "move" the sinc function generated by the incoming signal within the computational space in which the signal is processed.

The second stage of the simulation adds another axis to the computational space by taking a limited sample of the sinc function using a Gaussian function. Convergence of visual input fibers onto the lateral geniculate nucleus has made it possible to conceive of each geniculate cell as acting as a "peephole" sampling a part of the retinal mosaic (Pribram, K.H. 1991, p. 74; Hashemiyoony, R. & Chapin, J. 1996). In the somatosensory modality, a similar convergence onto the principle nucleus of the trigeminal nerve in the brain stem makes it possible to consider the cells in the ascending trigeminal pathway as sampling the mystacial mosaic. The Gaussian represents such a sample, a peephole, and has the advantage that its Fourier transform is also a Gaussian and thus can be readily applied to the spectral domain. When this sample represents the output of a single neuron it is limited by the spatial extent of the local field potentials fluctuating among that neuron's dendrites. When a surface distribution is modeled

from multi-unit bursts, the spatial constraint is assumed to portray a greater reach. Sampling, which manifests as a point process, is performed by the generative activity of the axon hillock, which, due to the upper and lower temporal limits of spike generation, functions as a bandpass filter. This filter is multiplied with the sinc function to yield a display of the surface distribution.

Figures 1c and d, 2c and d and 3c and d depict distribution and contour maps derived from these simulations. Note the close fit to the experimentally derived surface distributions and contours shown in the difference manifolds of Figures 1e and f, 2e and f, and 3e and f. Statistical analyses are presented in Table 1. A total of 48 surface distributions were experimentally generated. Of those three were essentially flat. Of the remaining 45, we simulated six; all but two of the remaining 39 have a shape that can be seen to be successfully simulatable with the technique described.

The surface distributions derived from our data are constrained by two orthogonal dimensions: one dimension reflects the spatial frequency of the stimulus and the other its temporal frequency. Thus, our Gabor functions are three-dimensional rather than five-dimensional since only one spatial dimension was used to stimulate the whiskers. In a subsequent experiment, we used a two dimensional spatial input, that is, we used grooved discs presented at various orientations. We are currently exploring possible visual and algebraic representations of the resulting five (2 spatial, 1 temporal, and 2 spectral) dimensional hyperspaces. Because spatial and temporal variables constrain the spectral response, a Gabor-like (Gabor 1946) rather than a simple Fourier (spectral) representation describes our results. The Gabor-like representations (2D spatial, 1D temporal and 2D spectral), which are in a class of five dimensional informational hyperspaces portrayed by Jacobi delta functions, or by Hermite polynomials such as Wigner distributions (reviewed by Pribram, 1991) have in common a distributed processing topology. Chapin and Nicolelis (Chapin, J.K. and Nicolelis, M.A.L. 1995) tested this distributed characteristic using a principal component analysis of multi-unit recording. They found that adding more units enhanced separability of factors but did not add any new factors. Their evidence supported the conception that the functioning of the somatosensory system (even in the thalamus) becomes distributed. Thus, in their experiments, as in ours, the surface distributions of

field potentials obtained from recordings made from the somatosensory cortex appear to be similar to those demonstrated in the primary visual cortex (Daugman 1990; Pollen & Taylor 1974; Pribram & Carlton 1986; Pollen & Gaska 1996). This suggests that such a processing medium is ubiquitous in cortical networks.

Gabor Elementary Functions: The Quantization of Brain Information Processing

During the 1970's it became apparent that Gabor's notation applied to the cerebral cortical aspect of sensory processing. The most elegant work was done with regards to the visual system. A recent review by Tai Singe Lee (1996) in the IEE casts these advances in terms of 2D Gabor wavelets and indicates the importance of constraining frames (such as orientation selectivity) and specifies the phase space sampling schemes needed for image reconstruction. For the monkey, the physiological evidence indicates that the sampling density of the visual cortical receptive fields for orientation and frequency provides a tight frame representation through oversampling. Lee develops his evidence as follows:

On the theoretical side, [the] important insight . . . advanced by Marcelja [1980] and Daugman [1980; 1985], [is] that simple cells in the visual cortex can be modeled by Gabor functions [can be used as a starting point for developing a theory of efficient reconstruction of an image. The 2D Gabor functions proposed by Daugman are local spatial bandpass filters that achieve the theoretical limit for conjoint resolution of information in the 2D spatial and 2D Fourier domains.

Gabor [1946] showed that there exists a "quantum principle" for information: the conjoint time-frequency domain for 1D signals must necessarily be quantized so that no signal or filter can occupy less than a certain minimal area in it. This minimal area, which reflects the inevitable trade-off between time resolution and frequency resolution, has a lower bound in their product, analogous to Heisenberg's uncertainty principle in physics. He discovered that Gaussian-modulated complex exponentials provide the best trade-off.

The original Gabor elementary functions, in the form proposed by Gabor [1946], are generated with a fixed Gaussian while the frequency of the modulating wave varies. These are equivalent to a family of "canonical" coherent states generated by the Weyl-Heisenberg group. . . . A signal can be encoded by its projection onto these elementary functions. This decomposition is equivalent to the Gaussian-windowed Fourier transform.

Daugman [1980;1985] generalized the Gabor function to the following 2D form to model the receptive fields of the orientation-selective simple cells. The 2D Gabor function is a product of an elliptical Gaussian and a complex plane wave. The careful mapping of the receptive fields of the simple cells by Jones and Palmer [1987] confirmed the validity of this model. Mathematically, the 2D Gabor function achieves the resolution limit in the conjoint space only in its complex form. Since a complex-valued 2D Gabor function contains in quadrature projection an even-symmetric cosine component and an odd-symmetric sine component, Pollen and Ronner's [1981] finding that simple cells exist in quadrature-phase pairs therefore showed that the design of the cells might indeed be optimal. The fact that the visual cortical cell has evolved to an optimal design for information encoding has caused a considerable amount of excitement not only in the neuroscience community but in the computer science community as well. Gabor filters, rediscovered and generalized to 2D, are now being used extensively in various computer vision applications [Bovik, Clark & Geisler 1990; Lee, Mumford & Yuille 1992].

Recent neurophysiological evidence [DeValois & DeValois 1988] suggests that the spatial structure of the receptive fields of simple cells having different sizes is virtually invariant. Daugman [1993] and others [Bovik, Clark & Geisler 1990; Porat & Zeevi 1988] have proposed that an ensemble of simple cells is best modeled as a family of 2D Gabor wavelets sampling the frequency domain in a log-polar manner. This class is equivalent to a family of affine coherent states generated by the affine group. The decomposition of an image f into these states is called the *wavelet* transform of the image A

particular Gabor elementary function can be used as the mother wavelet to generate a whole family of Gabor wavelets.

[However,] many questions, originally posed by Daugman [1985], about how the degrees-of-freedom which create the "coding budget" in the visual cortex are allocated and constrained, such as the trade-off between orientation sampling and spatial sampling, have remained unanswered. We here address and propose answers to those question.

In this paper, we first derive a class of 2D Gabor wavelets, with their parameters properly constrained by neurophysiological data on simple cells and by the wavelet theory. We extend Daubechies' completeness criteria on 1D wavelets to 2D and apply such criteria to study the physiologically relevant family of 2D Gabor wavelets. By numerically computing the frame bounds for this family of wavelets in different phase space sampling schemes, we elucidate the conditions under which they form a tight frame. We find that the phase space sampling density provided by the simple cells in the primary visual cortex is sufficient to form an almost tight frame that allows stable reconstruction of the image by linear superposition of the Gabor wavelets with their own projection coefficients, and provides representation of high resolution images using coarse neuronal responses. Finally, we demonstrate these theoretical insights with results from image reconstruction experiments.

Lee, 1996, pp. 1-2

Running his simulations, Lee came up with a surprising conclusion:

Physiological data suggest that the cortical sampling density is far greater than the parsimonious sampling density required for complete representation. In fact, it is dense enough to form a tight frame within a three to five octaves frequency band at each eccentricity, providing an over-complete and redundant representation of the retinal image within that frequency band. We have demonstrated there are at least two advantages to such a redundant

representation: first, an image can be represented and easily reconstructed as a linear superposition of the receptive field structures of the simple cells weighed by their firing rates; second, high precision information can be computed and stored by a population of low-precision neurons. (p. 12)

The results . . . show that two or three orientations are sufficient for complete representation of the image. Why, then, does the brain construct a tight frame? . . . Could the redundancy provided by a tight frame reduce the "resolution burden" of the cortical cells? Suppose a neuron's firing rate is limited in resolution, probably to three bits or four bits. (p. 11)

In fact, temporal coding carried in the spike train of a single neuron is more often $\frac{1}{2}$ a bit or less (Richmond & Opticon 1987). Finally, from Lee:

. . . the visual cortex is primarily concerned with extracting and computing perceptual information such as segmenting a scene [Lamme 1995; Lec, Mumford & Schiller 1995; Lee, Lamme & Mumford (Unpublished)], rather than representing simply the retinal image. The [receptive fields in] simple cells, modeled by Gabor wavelets, with the redundancy provided by a tight frame, facilitate these computations by providing an ideal medium for representing surface texture and surface boundary with high resolution. (p. 12)

We observed that even with such a coarse sampling density of the phase space, the original image can be reasonably reconstructed. The degradation of the image representation is graceful with the decrease in the resolution of the representational elements.

Evidence on Phase Encoding

Issue No. 2. Regarding the processing of the phase of the input by the sensory cortex, DeValois and DeValois (1988) have reviewed their own extensive work and that of others on the encoding of spatial phase regarding spatial localization (ibid. Chapter 8, p. 239). As they indicate, both absolute and relative temporal phase are unimportant in single channel

audition. However, as shown by Békésy, the spatial stereo effects of two or more channels and the projection of the sound image away from the sound source are accomplished by adjustments of the relative spatial phase among these sources. In addition, I wonder if our appreciation of the difference in a performance by a master pianist and an extremely proficient student may not hinge on just such a phase encoding process. The situation is similar for vision. Relative phase between a particular frequency and its double and triple plays a significant role in pattern processing such as vernier sharpening of discrimination of textures and binocular depth perception. For the most part, relative phase among low (1-3 cycles for degree) frequencies is responsible.

In addition to spatial phase, there is a temporal phase among temporal frequencies that determine directional processes in vision. When bidirectional inputs are out of phase with each other (relative phase) by a quarter cycle in both space and time they can create unidirectional outputs (see e.g. Watson & Ahumada 1983). As noted, relative spatial phase is due to spatial disparities among low spatial inputs to frequency cortical cells. Spatial quadrature (quarter cycle disparities) among neighboring cortical cells was demonstrated by Pollen and Ronner (1981). Temporal quadrature has also been described, beginning in cells of the lateral geniculate nucleus and persisting at the cortical level. Again it is the low frequencies that code the phase lags and leads. Important was the finding that reversal of the preferred direction occurred above 4 Hz as the phase difference reached a half cycle. Dramatic reversals were avoided because the averaged lagged response was much weaker than the averaged non-lagged response. (Saul & Humphrey 1992) These relative phase effects at low temporal frequencies are properties of the same cells (X or "simple" cells, Pribram, Lassonde & Pitto 1981) that encode relative spatial phase.

More needs to be done to determine the conditions under which phase encoding becomes useful. Phase encoding is now being examined in the somatosensory cortex using simultaneous recording from two or more electrodes. Of special interest are the conditions under which the computations in phase space remain linear and under what conditions non-linearities prevail (Kyriazi & Simons 1993).

The neurophysiological community has come to terms with the distributed nature of what can be conceptualized as the "deep structure" of cortical

processing (Pribram 1997). The accepted view is that distribution entails the necessity of binding together the disparate sites of processing. Binding needs to be accomplished by temporal synchronization of spatially distinct oscillating neural processes. But as seen from the quotation above, sparse sampling of the neural phase space is all that is required. Taken together with the finding that each receptive field in the sensory cortex is selective of a variety of sensory dimensions, binding as such becomes unnecessary. Rather, a spatial pattern involving an ensemble of neurons can select a currently appropriate combination from the more or less haphazardly conceived variety of available dimensions.

The emphasis has been that under the conditions which produce binding, no phase lead or lag is present. If, however, ensemble coding is the rule, phase can become important. In fact, Saul and Humphrey (1990; 1992) have found cells that produce phase lead and phase lag in the cortical processing initiated by them. In the somatosensory system Simons and his group (1993), analyzed the timing of the thalamocortical process to show how it enhances "preferred" features and dampens "non-preferred" ones -- that is, it sharpens sensory discrimination. The process thus can act as a frame that "captures" relevant features of combination of features. These results give promise to Gabor's prediction that we might find the solution to sensory (image) processing in the formalism, and perhaps even in the neural implementation of quantum information processing.

The Quantum Level

Issue No. 3. 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, the teledendrons, 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.) Thus, spine head polarizations passively spread to interact with each other via extra- as well as via the intracellular cable properties of dendrites. 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.) 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. (Hammeroff 1987; Penrose 1994.) The extra neuronal 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 (Hyden 1965). 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 formed by "lipids which form a fluid matrix within which protein molecules are embedded -- the lipids can move laterally at rates of 2 μ m/sec; protein molecules move about 40 times more slowly (50 nm/sec or 3 μ m/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 turpor to the extracellular space" (Shepherd 1988, pp. 45-46).

On the basis of these considerations, Jibu, Hagen,

Yasue and I propose that a perimembranous process occurs within dendritic compartments during which boson condensation produces a dynamically ordered state in water. This proposal originates in the work of Umezawa and his collaborators Ricciardi, Takahashi and Stuart. We have gone on to speculate that as each pattern of signals exciting the dendritic arborization produces a macroscopic, ionically produced change of the charge distribution in the dendritic network, it triggers a spontaneous symmetry breaking of a radiation field (a boson condensation) 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 physical substrate of the interactions among polarizations occurring in dendritic spines.

Ordered Dynamics in Perimembranous Region of Dendritic Membranes. Our principal concern is to account for the existence of distributed patterns of activity in dendritic arborizations by proposing a role for the extracellular fluid outside dendrites. These distributed patterns serve as an ideal substrate for experienced perceptual awareness and subsequent storage of that experience. Especially, we focus on the dynamically ordered structure of water in the perimembranous region immediately adjacent to the dendritic membrane. Detailed analysis of the dynamically ordered structure, meaning here a certain systematic pattern of dynamics of water in the perimembranous region, requires a fundamental theoretical framework, because thermal fluctuation and dissipation of water molecules in the perimembranous region are 10^6 as small as that of bulk water. It is a quasi-two-dimensional region far from thermal equilibrium, and the conventional theoretical framework of statistical physics can no longer be applied. We have to rely on a more fundamental theoretical framework of physics to investigate the dynamically ordered structure of perimembranous water.

Furthermore, the physical substrates taking part in the ordered dynamics would not be restricted to matter composed of atoms and molecules. It is most plausible that the radiation field (i.e. the field of photons; the electromagnetic field) plays an important role in

realizing the dynamically ordered structure in the perimembranous region. Therefore, we will take into account not only the extracellular fluid but also the radiation field as physical substrates for the ordered dynamics. As the extracellular fluid is essentially water containing several kinds of ions, it is natural to regard the perimembranous region as a quasi-two-dimensional array of water molecules with "impurity" (i.e. ions) overlaying the outer surface of dendritic membranes. The dynamically ordered structure of water may be easily illustrated as a systematic pattern of dynamics of water molecules. Indeed, several authors developed physical theories of water manifesting ordered dynamics. However, the radiation field has been regarded to play only secondary roles. But, as will be shown below, it binds water molecules dynamically with each other as a gauge field, and coherent emission of photons (i.e. energy quanta of radiation field) follows the ordered dynamics of water molecules.

In our present investigation of the dynamically ordered structure in the perimembranous region, we show that the radiation field plays not only secondary roles but a principal role as an ideal substrate accounting for the distributed saltatory aspects of dendritic processing. In other words, the radiation field manifests two distinct modes; a normal wave mode with real wave number and an evanescent wave mode with imaginary wave number. The former is essentially the well-known part of the radiation field binding water molecules dynamically with each other, making up the dynamically ordered structure of water. The latter is the damping part of the radiation field corresponding to a leak field which can be usually neglected in the case of bulk water but certainly not in the present case of a thin layer of water in the perimembranous region.

Superconductive Properties. In the body of the presentation (Jibu et. al 1996) from which this is an excerpt, we have shown that the high-temperature boson condensates of evanescent photons in the perimembranous region immediately adjacent to the dendritic membranes can be understood as a description of distributed saltatory processing in dendritic arborizations manifesting nonlocality. The dynamically ordered structure of water in the perimembranous region realized by the spontaneous symmetry breaking mechanism ensures the existence of such boson condensates. As those boson

condensates of evanescent photons are directly related to the quantum dynamics of the radiation field, certain superconducting phenomena could take place there. Indeed, the longitudinal mode of the radiation field plays the role of the order parameter characterizing the macroscopic dynamics of superconducting media, because it is locked to the phase of any matter field with electric charge through the gauge transformation.

Recall that the dendritic membrane is composed of two oppositely oriented phospholipid molecules. Thus, not only does the outer layer provide for hydrophilic extracellular processing, but the inner layer also makes possible an ordered water medium within the dendrites (and their spines).

Consequently, we can expect that, within the patch (or compartment) of a dendrite (including its spines) that falls within the coherence length of the ordered water, a couple of outer and inner perimembranous regions separated by a thin layer of cell membrane form an Josephson junction, that is, a sandwich-structured junction of two superconducting regions weakly coupled with each other through the membrane of means of quantum tunneling mechanism. The Josephson junction is a well-investigated superconducting device which is revealed to maintain specific superconducting phenomena called Josephson effects. The existence of Josephson effects in general biological cells had been suggested theoretically and several positive experimental evidence were reported. There, however, emphasis is put mainly on the extraordinary sensitivity of the superconducting current across the Josephson junction (i.e. Josephson current) to the imposed magnetic field. Such a magnetic Josephson effect can be an important clue as not only an indirect evidence of the existence of the high-temperature boson condensate but also a possible mechanism explaining the high sensitivity of the brain to the weak magnetic field. Besides the magnetic Josephson effect we have another one typical for the Josephson junction; that is, an electric Josephson effect. The latter plays an important role in realizing the nonlinear network of superconducting current among the brain cells as can be seen as follows:

Let us focus on a domain of the dendritic membrane smaller than the coherence length l_c in which the sandwich-structured Josephson junction is realized in terms of the boson condensates of evanescent photons in the perimembranous regions outside and inside the membrane. The electric potential difference $U = U(t)$ between the outer and

inner surfaces of the membrane can be thought of as the voltage across the Josephson junction. Then, the standard quantum field theoretical treatment of the electric Josephson effect yields that the Josephson current induced by the voltage $U(t)$ is given by

$$J(t) = J_0 \sin\left(\theta_0 + \frac{q}{h} \int_0^t U(s) ds\right). \quad (5)$$

where J_0 , θ_0 and q are certain constants (Yasue 1978). The circuit equation for the Josephson junction is therefore given by

$$C \frac{dU(t)}{dt} = -J(t), \quad (6)$$

where C stands for the capacitance parameter of the membrane. Introducing a new variable

$$W(t) \equiv \theta_0 + \frac{q}{h} \int_0^t U(s) ds, \quad (7)$$

we can rewrite the above equation as follows:

$$\frac{d^2 W(t)}{dt^2} = -\frac{J_0 q}{Ch} \sin W(t). \quad (8)$$

This is a nonlinear differential equation of the same form as the classical equation of motion for the physical pendulum, and has an oscillatory solution $W = W(t)$ represented implicitly by the elliptic function. Correspondingly, the membrane electric potential difference $U(t)$ manifests a self-excited oscillation $U(t) = \frac{h}{q} \frac{dW(t)}{dt}$ characteristic to the Josephson junction.

This is called the Josephson oscillation.

As there are extremely many Josephson junctions in the totality of perimembranous regions among the brain cells, we can think of a huge nonlinear network of superconducting currents across the Josephson junctions among the brain cells. We can expect that a considerable number of synchronized Josephson oscillations would result in realizing the macroscopic electric potential oscillations measured by microelectrode recordings of sensory activated dendritic fields. The fact that the Josephson oscillation is extraordinarily sensitive to the magnetic field imposed on the Josephson junction might explain the experimental finding that the human brain can be

influenced by small variations of the Earth's magnetic field.

Memory. Before closing our speculations on boson condensate of evanescent photons in the perimembranous region immediately adjacent to the dendritic membranes, it is worthwhile to delineate possible transformation of the distributed saltatory dendritic process into storage. The crucial point is 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 clear: There are three types of ions, that is, M-ions, C-ions and B-ions. This classification is made upon the effect of the ion on the dynamically order structure of water. However, the effect of an ion on water molecules is essentially due to the electromagnetic interaction of Coulomb type, and so its strength depends highly on the distance between each water molecule and the ion in question.

The above classification, therefore, can be regarded also as a classification upon the size of the ion: Ions whose radius is smaller than that of the water molecule are M-ions, and they do not disturb the dynamically order structure of water. Na^+ and Ca^{2+} ions are M-ions. Those whose radius is approximately the same as that of the water molecule are C-ions, and they play the role of water molecules in realizing the dynamically ordered structure of water. In other words, C-ions can be mixed with water molecules in the dynamically ordered state. K^+ ion is a C-ion. Those whose radius is larger than that of the water molecule are B-ions, and they disturb the dynamically ordered structure of water considerably. If there are B-ions in the perimembranous region, then the system of the radiation field and water molecules will suffer from dynamical disorder and so the dynamically ordered structure of water manifests defects. Cl^- ion is a B-ion.

Recalling the fact that K^+ ions and Na^+ ions show higher populations inside and outside the brain cell, respectively, the normal ionic environment of the cytoplasm and extracellular fluid might not disturb the dynamically ordered structure of water in the perimembranous region immediately adjacent to the cell membrane. However, Cl^- ions disintegrated from the anesthetic molecules can be thought to make many defects in the dynamically ordered structure of water,

and consequently the patient loses consciousness during general anesthesia.

We consider the normal environment in which we have only M-ions and C-ions in the perimembranous region. There, the dynamically ordered structure of water is maintained by the spontaneous symmetry breaking mechanism. Both the "apparent" dynamically ordered structure of water and the "evanescent" one of the boson condensate of evanescent photons play a role in the distributed saltatory processing occurring in dendritic arbors. However, it seems evident that the brain can stabilize the process over iterations that associate current input signals with the residuals remaining from prior inputs. For completing our quantum field theoretical approach we have to describe the possible mechanism of stabilizing the dynamically order structure of water and the boson condensate of evanescent photons in the perimembranous region immediately adjacent to the membrane.

It has been shown theoretically that the boson condensate of evanescent photons can be coated selectively by specific molecules and ions (Del Giudice, Doglia, Milani & Vitiello 1985; Del Giudice, Doglia, Milani, Smith & Vitiello 1989; Del Giudice, Doglia, Milani & Vitiello 1986). Such a molecular coating makes the dynamically ordered structure much more stable, and as a result the physical substrate for memory can be created. Namely, the more the dynamically ordered structure of water and the boson condensate of evanescent photons is molecular coated, the more it is made stable. The transformation mechanism of processing an input of signals into memory can be thus aided by the molecular coating of the dynamically ordered structure of water and the boson condensate of evanescent photons. Actually it has been reported that the distributed pattern of such a molecular coating has been observed in the cerebellum of rats (Nakazawa, Mikawa, Hashikawa & Ito 1995).

Evidence that, indeed, patches of dendritic membrane become the site of memory storage comes from the work of Daniel Alkon and his associates (Alkon, D.L. & Rasmussen, H. 1988). Alkon has shown that local interactions among neighboring spines are responsible for the learning induced changes that give rise to classical conditional responses. The interaction between adjacent spine heads, as noted by Shepherd (1988), must proceed to a considerable extent extracellularly because of the high internal electric resistance of the narrow spine necks.

According to Alkon, the interaction is communicated intracellularly to the cell body which, in turn, generates factors that return 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). This reduction lasts for many days. "The ion flow changes seem to result from the movement of the calcium-sensitive enzyme [Protein Kinase C] PKC. In response to the changes in calcium-ion concentration and in another second messenger, diacyl glycerol, that accompany the association of temporally related sensory stimuli, PKC moves from the cell cytoplasm to the cell membrane, where it reduces K^+ ion flow" (Alkon 1989).

The protein target of the PKC enzyme is the GAP-binding protein that appears to be involved in regulating ion channels. "This 20 kilodalton protein may serve functions in the context of learning that are analogous to the functions [that] so-called G proteins assume in developmental and oncogenetic contexts."

A second enzyme, another calcium activated kinase known as CAM Kinase II also phosphorylates the 20 kilodalton protein target. This enzyme is concentrated at postsynaptic sites (including those on spine heads) throughout cortical dendritic trees.

The induction by these enzymes of changes in the cellular quantity of 20 kilodalton proteins is accompanied by increases in the synthesis of a number of species of mRNA. One of the species actually corresponds to the 20 kilodalton protein.

Both the extracellular and the dromic and antidromic 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 turpor produced by glycoproteins provides the necessary structure for holding perimembranous order water to which ions can adhere.

Internally, the dynamically ordered water can provide the substrate for dromic and antidromic superconductivity in the dendritic compartment activated by the temporal association of a conditional with an unconditional input signal.

Dynamically ordered water can also aid memory retrieval. One a physical substrate is formed in the perimembranous regions as a macroscopic domain of the dynamically ordered structure of water, we can make use of the emergence of Goldstone bosons as a

physical process involved in conscious memory retrieval, as originally proposed by Riciardi and Umezawa (Umezawa 1993) and Stuart, Takahashi and Umezawa (1978; 1979). Namely, when the system of the radiation field and the water molecular field suffers from even a weak perturbation due to a change of the charge distribution in the dendritic membranes induced by an external stimulus of a nature similar to that used in the perceptual process, the Goldstone bosons characteristic to the domain of the dynamically ordered state corresponding to the physical substrate for the delayed input-output processing that makes awareness possible. The physical process of conscious memory retrieval is postulated to be mediated by the Goldstone bosons (i.e. long-range correlation waves) with almost no energy requirement. The Goldstone bosons play a role in the replication of the original external stimulus. In this way, the existence of memory in terms of the domain structure of the dynamically ordered states of the system of the radiation field and the water molecular field can give rise, as in the initial processing of the stimulus, to the delay in processing that is coordinate with conscious experience.

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Figure Captions

Figures 1, 2, 3. Examples of local field surface distributions (1a, 2a, 3a) and their associated contour maps (1b, 2b, 3b) derived by cubic interpolation (spline) procedure from recorded whisker stimulation. The contour map was abstracted from the surface distribution by plotting contours in terms of equal numbers of bursts per recording interval (100 secs.). Each figure shows baseline activity (no whisker stimulation) at a given electrode location as a plane located in terms of number of bursts per 100 secs. The x axis represents temporal frequency (T.F.) in revolutions per seconds (RPS). The y axis represents spatial frequency (S.F.) in terms of the number of flicks per revolution (Flicks/R). Figures 1c, 2c and 3c are examples of simulated surface distributions of local field potentials and their associated contour maps (1d, 2d, 3d) to be compared with the empirically derived maps presented in Figures 1a & b, 2a & b, and 3a & b. Figures 1e and f, 2e and f, and 3e and f show the difference between the surface distributions mapped from the data and those mapped from the simulations. Note that the coordinates of the difference maps range from 0 upward while those of the surface distributions mapped from data and simulations range from a much higher level upward.

Table 1

		Min. Value	Max. Value	Mean Value	Std. Dev.
Fig. 1	Actual Bursts	579.5	955.6	703.8	113.68
	Simulation Bursts	625.7	955.5	746.7	103.9
	Difference	0.02	165.75	52.63	45.85
Fig. 2	Actual Bursts	230.5	384	318	28.02
	Simulation Bursts	233.9	384	291	33.82
	Difference	0.005	97.7	34.8	26.58
Fig. 3	Actual Bursts	416.8	725.8	537.9	68.79
	Simulation Bursts	417.4	755.8	505.2	80.74
	Difference	0.05	154.9	60.8	39.35

Table 1. Descriptive statistics from empirically derived (actual) and simulated surface distributions and accompanying difference distributions for Figures 1, 2 & 3. Note, in the figures, that the greatest differences between experimentally derived and simulated surface distributions occur due to slight differences in the placement of the peaks between the two.





