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Conscious awareness: processing in the synaptodendritic web

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Abstract

Evidence is presented which indicates that, at the level of conscious experience, information processing in the brain is basically Gabor-like rather than binary (as in Shannon's information measurement theory). The process takes place in a phase space created by a multiply interconnected web of teledendrons, synapses and dendrites. The axons of neurons sample the phase space to create cell assemblies. Assemblies are kaleidoscopic in that the same neuron can partake in a variety of patterns of neuron ensembles. This is much like the variety of patterns created by the features red sweaters, blond hair, or eyeglass wearing in a classroom. A particular student (or neuron) may participate in one or more (or none) of the patterns. The flexibility of conscious experience is attributed to sensory and cognitive challenges that drive the formation of processes in the teledendron-synapse dendritic web. When the formation of axonal patterns takes time (a temporal hold) because of the novelty of the input, they become experienced consciously.

Keywords: Consciousness; Dendritic web; Fourier transformation; Holography; Holonomic theory

1. Introduction

Philosopher David Chalmers (1996) distinguished hard from easy problems in discussing the ontology of "consciousness". He claimed that finding relationships

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between brain processes and conscious experience is the set of easy problems. He identified the hard problem as dealing with the experienced inner life of ourselves and of other individuals. I do not agree with Chalmers that the problems of relationships between brain processes and conscious experience are any easier or harder than other epistemological issues. I resolved the issue in the following manner.

Each of us is conscious of our own experience. We begin with this experience and from there build a body of knowledge by a series of trials. We attempt to validate our experiences by social interaction; we analyze them by taking them apart to understand the underpinnings of the experiences.

Our knowledge, thus, is formed through gaining additional experiences. We try to organize these experiences, these data, by classifying, categorizing them — a process often called inductive reasoning. Alternatively, we can take these data and treat them as facts (from *factum*, Latin for to make) and try to organize them into a structure consisting of formal deductions based on hypothesis testing.

The processes of induction and deduction, though they organize our knowledge, do not provide any really new ways to think about our data or allow any really new observations to be made. Our knowledge base is expanded through metaphor and analogy — abduction, as Peirce (1934) called it.

In this essay, I develop an organized data base, some hypotheses, and a metaphor to broaden perspective in terms of a theory that is intended to bring induction, deduction and abduction together. The theory is not completely formalized as yet into a hypothetico-deductive framework; rather it is stated as a thesis from which hypotheses can be derived.

Before moving into this discussion, it is worthwhile to note the variety of definitions of consciousness in use today. Our experience of the universe comes in *patterns*, and we tend to relate to these patterns — social patterns, physical patterns, and so on. This tendency constitutes the spiritual aspect of man's consciousness (and to some extent, we know what parts of the brain are involved in this tendency). In Western thought, we often refer to the sum of all these patterns as God. A related issue is the fact that in some languages and cultures, the term consciousness includes both consciousness and what in English we call conscience. Conscience in French means both consciousness and conscience. The same is true in German and to some extent in Spanish. Here, I will limit the discussion to the relationship of brain processes to our ordinary everyday conscious experience, as defined in English, and not the more global issues involved in other definitions.

2. The origins of conscious processing

Let us begin with what is known and generally accepted within the neuroscience community. The nervous system is made up of units. These units are usually called cells or neurons, and neurons have a cell body with branches coming from that cell body. One of these branches is chemically different and is usually somewhat larger than the other branches, and if it is large enough, it can support a nerve impulse, a depolarization of its membrane, which makes a sharp noise or a visual spike on our electronic equipment. These spikes — that is, nerve impulses — are taken as the currency of processing in the nervous system.

However, there is another, very different aspect to neural function that has been, to a large extent, ignored by the neuroscience community: the processing that goes on in the finer branches of the neuron. At the distal end of an axon where it synapses (makes a junction) with another neuron, it splits into branches, called teledendrons, which connect to the dendrites of another cell, its non-axon branches, through chemical synapses and electrical ephapses. The teledendrons and dendrites form a web of fine fibers in which processing occurs that does not involve nerve impulses. Rather, fluctuating (oscillating) polarizations — depolarizations and hyperpolarizations of the electrical potential differences in the membranes of the fine fibers — are the basis of such processing

My hypothesis is that what we become aware of, our conscious experience, is due to what is going on in this processing web.

When behavior becomes automatic, when we do not attend to it, behavior is organized by the generally accepted nerve impulse circuits, because input and output through the web has become readily matched and thus, rapidly paced. The web hypothesis is that we *become aware of* our conscious experience due to a delay between an incoming pattern of signals before it matches a previously established outgoing pattern. In this web, chemical as well as electrical patterns are able to influence processing.

The importance of the processing web with regard to human conscious experience is shown by the relative density of neurons in the cortex of a mouse and in the cortex of the human. Table 1 tells the story of the evolution of the cerebral cortex better than any other concise description. With a decrease in neuron density comes an increase in the number of connections per neuron. The branching of the axons and dendrites is vastly greater in humans, thus reducing the cell density. When corrected for body size and increase in non-projection (non-sensory-motor) cortex, this increase is roughly

Table 1
Density of neurons in the cortex of animals

Type of animal	Neuron density
Mouse	142.5
Rat	105.0
Guinea Pig	52.5
Rabbit	43.8
Cat	30.8
Dog	24.5
Monkey	21.5
Human	10.5
Elephant	6.9
Whale	6.8

Note: Neuronal densities in the motor cortex in various animals, based upon Tower (1954) and Tower and Elliot (1952).

correlated with an increase in the diversity of problems that can be solved by an organism. Thus, it is the connectivity, what I have called the synaptodendendritic processing web, that becomes more and more important during evolution leading to hierarchical levels of processing.

The rest of this essay deals with what is going on in the processing web, how it accounts for distributed functions in the brain, and how it can act as a substrate for conscious experience.

3. The holonomic theory

The hologram was invented by Dennis Gabor (1946) as a method for enhancing electron microscopy. The invention was purely mathematical, based on the Fourier transform. In a hologram, the "information" necessary to construct an image becomes distributed. To illustrate this, I use a slide projector. If one inserts a slide into the projector and shows a figure such as a view of a brain, then removes the lens from the front of the projector, there is only a bright area, nothing — no-*thing* — visible on the screen. But that does not mean there is no information in the area. The information can be re-visualized by placing a pair of reading glasses into the light beam coming from the projector. On the screen, one now again sees the figure — or with the two lenses of the eyeglasses one sees two figures which can be made to appear in any part of the bright area.

This demonstrates what is at the core of the holonomic theory. Neuroscientists have come to agree that brain processes are distributed, mainly because after brain injury, no specific memory traces are lost. However, both in animals and humans such lesions will produce specific deficits in the retrieval of entire classes (such as visual, auditory, tactile) of memories. It is the items — the engrams — of memory which have become distributed and so can be retrieved through some alternate non-damaged "channel". Thus, we can divide memory into a deep and a surface structure; the deep structure being distributed while the surface structure — the retrieval mechanism — is composed of highly localized nerve impulse circuits.

Deep, distributed memory process is holistic in a way that is totally different from the holistic process that Gestalt psychologists, biologists and Arthur Koestler (calling such organizations holons) were talking about (Koestler, 1967). This type of holism is based on the fact that the whole is greater than and different from the sum of its parts. The holographic view is different in that every "part" is *distributed over* the whole. And *every "part", therefore, contains the whole* — just as in the demonstration made with the slide projector and the reading glasses.

A somewhat similar arrangement is present in broadcasting — all channels are available everywhere within the broadcast area — the channels are distributed over the area, and all are available at each location. A momentary "cut" through the airwaves in any location would show a holographic organization — that is, the location contains all the information of all the broadcasts.

A more complete, formal definition of the holonomic theory is this: The holonomic theory of brain function is a cybernetic theory that relates information, control and self-organization. The measure of information is a Gabor-like wavelet rather than the BIT (which is a measure used in computer science). In aggregate, the Gabor wavelets constitute quantum holographic vector fields. Control over information flow in the brain is affected by the creation of temporary dominant foci of fields of electrochemical activity. Self-organization results from the lasting influence of these controls on the distribution of information.

Gabor wavelets will be discussed in some detail in the section that follows.

4. Neurons as units versus patterns of neurons

Now, if we look once more at neurons in the sensory systems, we need to emphasize another aspect of processing: Each neuron is sensitive to a variety of sensory inputs; neurons are not just detectors of a single aspect of perception. In the primary visual cortex, for example, every single neuron is sensitive to spatial frequency, orientation, changes in luminance, direction of movement, velocity and acceleration — there are all kinds of propensities of the cells to respond to a variety of sensory dimensions such as these.

Neurons do not operate singly, and in order to understand distributed structure, we examine ensembles of neurons or cell assemblies. When we record from ensembles — cell assemblies — we find that even in the primary visual cortex, sensitivities extend to whether the animal presses the right lever or the left lever, whether or not the press was reinforced or non-reinforced when a monkey is solving a problem (Pribram, Spinelli & Kamback, 1967).

Take as a metaphor an auditorium full of people. If all those people wearing red sweaters or shirts were to raise their hands, a pattern would emerge. Then if only those people wearing eyeglasses were to raise their hands, another pattern would emergence — some of the same people wearing eyeglasses also have red sweaters, so there is an overlap of persons generating the patterns — just as there is an overlap of neurons with multiple propensities to generate patterns in the brain. Hebb (1949) characterized these overlapping functions of cell assemblies in terms of phase sequences. Cell assemblies are kaleidoscopic. The same neuron can partake of different assemblies — that is, become incorporated within different assemblies at different times. Which particular ensemble is assembled can be sensory driven by input from sensory receptors or cognitively driven by inputs from other brain systems.

Phase turns out to be critical to the flexibility in assembling neural ensembles. The assembly is created by a holographic-like distributed process. Such a process occurs within the teledendron-synaptodendritic web within each circuit. The web extends beyond the confines of single neurons, thus making possible the flexibility in assembling circuits.

Functionally, the web is primarily composed of oscillating de- and hyper-polarizations of dendritic membranes. Nerve impulses are rare and have little or no role to play in the web. A story makes this important concept memorable.

At an International Physiological Congress in New Delhi, India, the keynote speaker was Sir Alan Lloyd Hodgkin, who had received the Nobel prize for modeling the origin and propagation of the nerve impulse. Hodgkin stated that after receiving the prize he wondered what to do next. He noted that what he really wanted to research was brain cortical function and hit upon the idea that the retina of the eye was anatomically and functionally just like a piece of cortex, which he humorously suggested was "placed outside the skull just for neurophysiologists to study". He had been recording from the retina for a decade and had yet to see a nerve impulse. He concluded that visual processing up to ganglion layer is devoid of nerve impulses and is composed purely of hyper- and depolarizations! Perhaps, he noted, this is a lesson to be taken seriously by those studying cortical processing.

This non-impulse aspect of retinal and cortical processing has, for the most part, been neglected. Notable exceptions have been investigations by G. Bishop, F.O. Schmitt, K. Pribram and recently T. Sejnowski. Polarizations fluctuate, and these oscillations occur at specifiable frequencies. The brain electrical activity recorded from the scalp (the EEG), for the most part, reflects these fluctuating polarizations (Creutzfeld, Watanabe & Lux, 1966). Frequencies occurring in different parts of the web can synchronize or they can show phase differences which can be seen both in the EEG and from microelectrodes.

Frequencies of oscillation of membrane depolarizations and hyperpolarizations originating in different locations produce designs that can be conceptualized either statistically or alternatively as wave forms that intersect with one another, creating patterns of nodes of where interference and reinforcement among the waves forms occur.

These patterns are the key to understanding the operations of the processing web. The patterns of nodes are described by the Fourier transformation, and there is substantial evidence from recordings made of receptive dendritic fields of neurons in the primary visual cortex that the Fourier transformation describes these fields (DeValois & DeValois, 1980; Glezer, 1995; Pollen & Gaska, 1997; Pribram, 1991). The Fourier transformation also describes the mathematical foundations of the hologram as invented by Gabor. Thus the holographic metaphor is used to model the processing web.

But the Fourier transform has two problems that must be considered in the development of such a model: (1) Fourier transformations involve infinities; and (2) holograms involve the encoding of phase (that is, the transform produces complex numbers which encode the square of intensity and phase relations among intensities).

To take up the first of these problems, during the 1970s it was realized that the sinusoidal fluctuations composing the Fourier transform had to be constrained; receptive dendritic fields do not extend to infinity. A ready answer to this problem had been given by Gabor in dealing with a totally different problem, efficient telephone communication across the Atlantic cable. Gabor constrained the sinusoids by a (space) time Gaussian and found that the maximum compressibility of a message is $\frac{1}{2}$ wavelength. For this Gabor used a Hilbert phase space in which frequency of a wave form provided one axis, spacetime the other. Gabor called these units logons or quanta of information. His reason for this name is that Gabor used the same mathematics that Werner Heisenberg had used to define microphysical quanta.

Of course, this does not mean, though it does not preclude the possibility, that quantum-type processes are involved in telecommunication or in the processing web.

Today we substitute the term *wavelets* for Gabor's logons. We have combined Gabor's insights on holography and on communication into what is now called quantum holography in image processing such as when magnetic resonance imaging (MRI) is described (Schempp, 1998). For processing in the brain's teledendron-synapse-dendritic web as mapped by recording receptive fields of neurons, I have used the term holonomy (Pribram, 1991, prologue).

For the second of the problems above for the application of the Fourier transformation to modeling the processing web, there are fewer data. Mapping the phase between EEG wave forms recorded from the scalp has awaited the application of considerable computer power (see Rodriguez, George, Lachaux, Martinerie, Renault & Varela, 1999). With regard to receptive fields, mapping has awaited the facile use of multiple microelectrodes. But some data are available: The primary work of Pollen (Pollen & Taylor, 1974; Gaska, Jacobson, Chen & Pollen, 1994) and the more recent studies on phase encoding in the geniculo-striate visual system and elsewhere (Saul & Humphrey, 1992a,b). Such studies are bound to accelerate in the immediate future now that multiple microelectrode arrays are more readily available and the computer power is at hand to analyze the results. (My laboratory is actively engaged in both the scalp recordings and microelectrode studies.)

Some members of the neural network community have now also become interested in discovering the conditions which make phase encoding necessary for perception. For instance, Sejnowski has reviewed the evidence for the importance of dendritic processing and in another venue has shown that Independent Component Analyses produces Gabor-like filters (Bell & Sejnowski, 1999; McKeown et al., 1998). These filters utilize phase which is necessary for the perception of edges.

5. The spectral processing domain versus the spacetime, objective "real world"

When we deal with Fourier transformations and phase — and even to a large extent with Gabor functions — we move out of the space-time domain and into the spectral domain. Using the hologram and the slide projector as an example again, the question might be asked, as it has been, by Will Hoffman and others: What is the lens which focuses processing in the brain, moving us back into our accepted, "real world" order of space and time?

The answer, I believe, lies with processing by the motor cortices, those areas around the primary sensory areas which, when stimulated, produce motor responses. For instance, around the visual sensory cortex is a area, the peri-visual, which produces head and eye movements when electrically stimulated; around the auditory sensory area there is an electrically excitable area which produces ear movements (in rabbits and deer); and of course, the somatosensory cortex is accompanied by the classical precentral motor cortex. These motor systems operate back on the visual sensory systems in the following way.

The eye is in constant motion, micro-nystagmoid tremor-like oscillatory movements are always present. Should they cease we would see nothing. Experiments in which the optical image projected on the retina is stabilized[3] fades away within approximately 30 s. Oscillations lead to point attractors (dots) in phase space — that is, everywhere within the visual system's sensory projection dots are formed. When more encompassing eye and head movements, controlled by the peri-visual motor system, are executed, these dots become grouped according to the patterns generated by the relative movement of the retina with respect to the optic flow — the moving optical image created by the lens of the eye. Grouping creates the perception of entities, objects, as shown by the experiments of Bernstein (1967) and Johansson (1978).

Bernstein's experiments were performed with people dressed in black leotards photographed (in cinema) against black backgrounds. White dots were attached to their leotards at each joint. These dots were registered on the movie film as sinusoidal wave forms. Bernstein found that by a Fourier procedure he could accurately predict the next movement in the series.

Johansson used a similar setup and added computerized Fourier generated patterns of groups of dots. Easily recognizable "objects" were created on the oscilloscope face — in one example, a boy and girl dancing could readily be recognized from as few as a dozen dots grouped according to the movements executed by the dancers.

A demonstration can bring home the difference between a subjective experience (an image) and the perception of an object. With your eyes closed, I repeatedly touch your hand with a key, you describe the experience as "my hand is being poked". However, if I place the key in your hand and you close your hand around and manipulate it, then you identify an objective entity, "Oh, that's a key". Movement changes the subjective experience into an objectified entity in the world "out there".

6. Conclusion

This has been a brief exposition of the evidence extensively reviewed in Pribram (1991) part I, lectures 1-5) for the sensory-driven part of the holonomic brain theory. The theory took origin in the metaphor of holography because of the distributed nature of brain memory processes and because of the ready invertabilitiy between a powerful spectral processing domain and the "objective" spacetime projected from this process. On the basis of data limiting the spatial and temporal extent of the spectral process, the holographic metaphor was modified in favor of the holonomic theory presented here. Gabor's insights into communication (as well as his invention of holography) were used as a basis for the modification. The Gabor function (the wavelet) was derived by the same mathematics as that which characterizes quantum theory — thus Gabor called his unit a quantum of information, and today image

[3] Stabilization is accomplished by projecting a pattern onto a mirror pasted on the sclera (which is insensitive) and from there onto a screen.

processing such as that performed in Magnetic Image Processing is based on quantum holographic principles.

Evidence was presented that indicates that at the level of conscious experience, information processing in the brain is basically Gabor-like rather than binary (as in Shannon's information measurement theory). The process takes place in a phase space created by a multiply interconnected web of teledendrons, synapses and dendrites. The axons of neurons sample the phase space to create cell assemblies. Assemblies are kaleidoscopic in that the same neuron can partake in a variety of patterns of neuron ensembles. This is much like the variety of patterns created by the features red sweaters, blond hair, or eyeglass wearing in a classroom. A particular student (or neuron) may participate in one or more (or none) of the patterns.

Thus the flexibility of conscious experience is attributed to sensory and cognitive challenges that drive the formation of processes in the teledendron-synapse dendritic web. When the formation of axonal patterns takes time (a temporal hold) because of the novelty of the input, they become experienced consciously.

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