Fundamentals of Human Brain Function

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Human Species

The parts of the brain more significantly developed in humans than in other mammals are the frontal lobe and cerebellum, specifically, the prefrontal area of the frontal lobe and neocortical area of the cerebellum (Figure 1). Although it is easy to understand that development of the cerebellum is likely linked to fine motor skills, the biological drive leading to prefrontal development cannot be intuitively understood. A plausible answer is supplied by a famous individual on September 13, 1848, in the surrounding area of Cavendish, Vermont, USA.

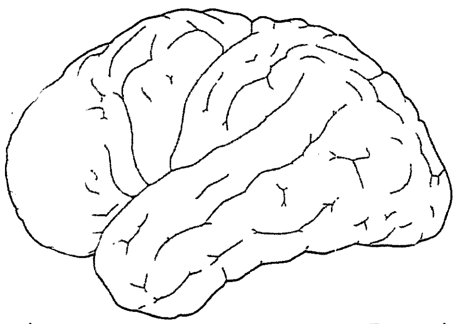

Figure 1 : Prefrontal area of the frontal lobe.

A foreman of a railway construction gang working for contractors preparing the bed for the Rutland and Burlington Rail Road suffered a serious accident. His name was Phineas Gage. An explosion of a charge he had set blew his tamping iron through his frontal lobe. He survived but lost almost all of the prefrontal area. Surprisingly, after having recovered from the acute condition, Gage did not show any particular neurological deficits. No paralysis, no language difficulties, no sensory disturbance. At a glance, he was a guy just like any other guy. However, his personality had dramatically changed. He was a totally different man. Whereas before the accident he had been a most capable and efficient foreman, after the accident he was irreverent, grossly profane, impatient, obstinate, capricious, vacillating, and unable to settle on any of the plans he had devised for future action.

This case is a clear illustration of prefrontal lobe function. The human is a mammal characterized by well a developed prefrontal lobe. Therefore, from the behaviorological aspect the human can be defined as a mammal with rationality, self control, intellect, capable of deliberate decision. Intriguingly, language is not included in the domain of prefrontal lobe function. Language does not appear to be a mandatory factor separating humans from others mammals.

Music and Language

The canary is one of the songbird species. However, only the male adult canary sings. This clear gender difference indicates that singing capability is a brain function likely related to reproductive function. From the neuroscientific standpoint, two aspects regarding canary singing are notable, namely: (1) the brain region specialized to singing is localized to one hemisphere; and (2) the repertoire of songs is acquired by learning. Following two entirely separate evolutionary lines, birds, believed to be descendants of dinosaurs, and humans developed a similar hallmark of brain functional organization, hemispheric specialization.

Music and language are processed virtually

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Figure 2：Functional images of the act of reading.

Activation maps associated with reading Japanese text and musical score reading are virtually identical, strongly indicating that language and music are almost identical functions for the brain.

identically in the human brain (Figure 2). Phonologically speaking, many birds speak human languages. Considering that the cerebellum in birds highly developed, this structure may be an important link in the evolutionary development of language (or musical) capabilities. Indeed, recent investigations on autism have demonstrated that the common structural abnormalities found in autistic children are immaturity of the cerebellum.

Human language is characterized by its highly functional contents, a clear distinguishing characteristic from the imitation "language" of birds. A like argument can be made for human music which contains highly functional contents, a component lacking in bird music. It is highly plausible, therefore, that human and birds faced extremely similar conditions for evolving fine motor skills essential for producing language and music. However, only humans, faced the additional evolutionary conditions leading to intellectual capability.

Departure from Localizationism

Modern brain science began with the description of expressive aphasia by the French neurosurgeon Pierre Paul Broca. Since then, higher function research has been focused on determination of the brain regions responsible for specific functions. Localizationists believe that the brain can eventually be understood as the linear sum of these deterministic functional units[1].

From the phenomenological point of view, there is no doubt that certain regional functional specificity exists within the brain. However, even if one were to accept the central dogma of brain science that the basic unit of all brain functionality is the neuron, it is abundantly apparent that localizationism will face inherent limitations at a certain point[2]. There are no Mozart recognition cells (or units) in the brain! The brain is a complex system and it is impossible to consider its function as the linear sum of deterministic functional units. Localizationism is in effect a practical compromise by brain scientists because of the limited methodologies available for studying brain functionality. The methodologic limitations are especially keen when one considers the metaphysical concept of the brain known as the mind.

The brain is a physical reality. Therefore, even as the mind is a metaphysical product of the brain as a dynamical complex system, there must be an identifiable structural organization responsible for this phenomenology. The mind, too, cannot escape from the axiomatic condition of biological realization. Many investigators have searched for a scientific definition of mind" and failed. Psychologists and behaviorologists analyze the brain as a black box, while computational neuroscientists created theories which are intangible. Modern brain science is in desperate need of a breakthrough.

Complex system and Self-organization

Lightning fast advancements in molecular biol-

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1 In a way, digital computers represent such a system.

2 The existence of "grand motor" cells has been clearly rejected in neurophysiology.

ogy impart the impression that genes define everything in biology. This notion is in a sense correct. However, this is not to say that genes contains the complete blue print providing all the deterministic details of processes of biological structure formation. The human brain contains more than one hundred billion neurons and 10^{14} synapses. Even without regard to the size of the genome, it can be easily deduced that a deterministic blueprint for connectivity of such an enormous number of networks is unrealistic. Existing scientific knowledge indicates that nature utilizes principal rules instead of complete deterministic descriptions to fashion a desired structure, namely, the rules of self-organization

The principal process of self-organization of structure formation is said to be in the form of the Markov chain (Figure 3). What the system does at point n is determined by the state at point n, $M_{(n)}$. The system needs not to have knowledge of how the system reached $M_{(n)}$. The next condition is determined based on the principal rule (*Rule M*) governing the system to create $M_{(n+1)}$.

$$M_n \xrightarrow{Rule\,M} M_{n+1}$$

Figure 3 : Markov chain

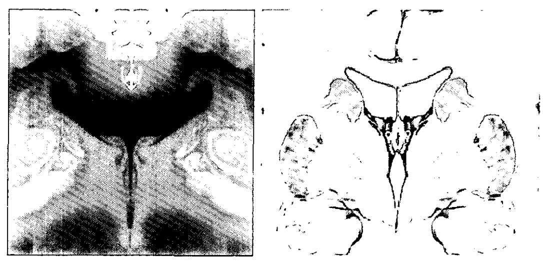
The brain is a representative of a complex system and self-organizes based on Markovian processes. Brain functionality can be seen as specific patterns created by self-organizing processes based on conditions defined by genes and the environment. Brain function is achieved by two interacting self-organizing processes, namely, self-organization of structure and self-organization of connectivity.

Brain Structure and Self-organization

The principal rule of self-organization governing brain structure was found to be free heat convection. Accordingly, brain shape can effectively be simulated based on the Boussinesq equation:

$$(\mathbf{v}\cdot\nabla)\mathbf{v} = -\nabla\frac{p^*}{\rho} - \beta\theta\mathbf{g} + \nu\Delta\mathbf{v}$$
$$\mathbf{v}\cdot\nabla\theta = \chi\Delta\theta$$
$$\nabla\cdot\mathbf{v} = 0$$

where $\chi = \kappa/\rho c_p$ represents thermometric diffusivity, β, the thermo-expansion coefficient, and ν, kinetic viscosity. The equation stands to effectively incompressible fluid of uniform density ρ, and the gradient of excess pressure is given by $\Delta p = \Delta p^* + \rho g$ (Figure 4).



Simulation **Schema**

Figure 4 : Heat convection and brain self-organization

There is strong implication that functional organization of the brain also utilizes the principal rule of heat convention.

Neural Network and Self-organization

As mentioned earlier, the sheer number of neurons and synapses preclude a deterministic blueprint for connectivity of such an enormous number of networks from being realistic. Therefore, as in the case of structure formation, self-organizing processes must play a significant role in developing functional connectivity of neurons.

Among various algorithms in the field of neural net, the concept which is generally referred to as Kohonen's map provides the most plausible self-organization processes creating associative memories, the configuration of which are virtually identical to those found in neurophysiological studies (Figure 5).

$$h_{rs} = \exp(-\frac{\|r-s\|^2}{\sigma^2})$$

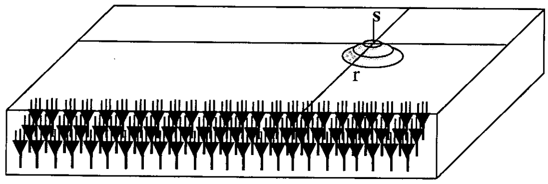


Figure 5 : Kohonen's map
hrs: neighborhood kernel

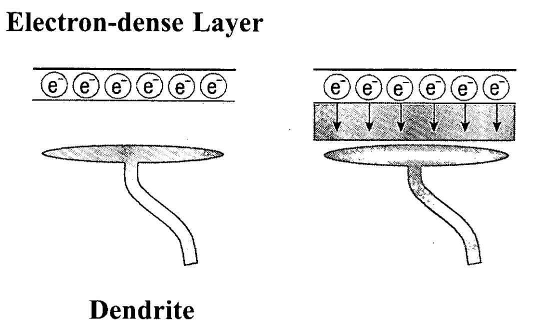


Figure 6 : ELDER

ELDER (Electron-dense Layer DEndritic Ramification) is a synapse-like functional unit formed between the primary dendrites of pyramidal cells and electron-dense layer formed by glial fibers. The electron dense layer is located just beneath the pia matter and faces the first layer of the cortex. The space between these two structures is maintained as a space of relatively low water content such that the electrons of the electron dense layer do not move towards the dendrites. Once a vortex wave arrives and the density of water content increases, the electrons will discharge and as a result the pyramidal cells are activated.

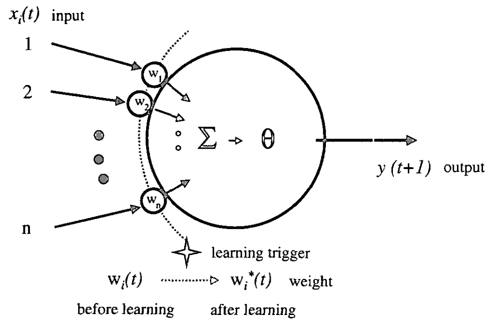
Brain Chip

The impasse in brain science was recently surmounted by the introduction of the Vortex Theory. This theory is not only capable of linking all neuro-phenomenology into a single fundamental concept of brain functional organization but it is also firmly based on biological and anatomical reality, the most important factors for any theoretical presentation in biology.

Vortex theory is formulated based on the concept that brain shape is defined by the self-organizational principle of free heat convention. The theory predicts a functional unit other than the neural network, in which glia play a critical role. One of the key elements proposed in the Vortex Theory is a synapse like structure formed by the primary dendrites of the pyramidal cells and electron-dense layer formed by glial fibers. Such a unit is referred to as ELDER (Electron-dense Layer DEndritic Ramification). The outer most layer of the brain immediately beneath the pia patter which contains ELDERS is referred to as LGS (lattice gas shell) (Figure 6). The functional unit of the brain in the Vortex Theory is termed the brain chip, analogous to that of the cerebellum (cerebellar chip).

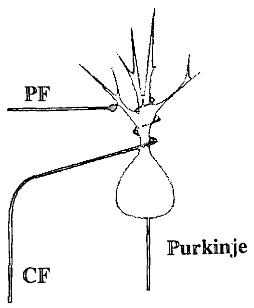
The brain chip represents a two-dimensional version of Ito's cerebellar chip. Similar to a cerebellar chip, the brain chip is organized around principal output neurons, namely, the pyramidal cells. Learning will be accomplished by altering transmission efficacy of a synapse onto pyramidal cells in the brain chip similar to that of Purkinje cells in a cerebellar chip. The climbing fibers equivalent functional unit is provided by the ELDER (Electron-dense Layer and Dendritic Ramification) unit containing LGS. The unit is maintained by the astrocytic assembly(aquaporin-4). An entropy-vortex wave, traveling within the passage ensured by self-organizing processes of the brain shape realized by Markovian advancement of radial glial fibers during brain development, provides the impulse equivalent to that propagated by climbing fibers in a cerebellar chip. The impulse produces a synchronized "learning trigger" to multiple pyramidal cells belonging to a single brain chip. The effectiveness of the learning trigger is dependent on the distance from the center of the unit as in the case of neighborhood kernel of the Kohonen's self-organizing map (Figure 7).

Figure 7 : Cerebellar Chip vs. Brain Chip

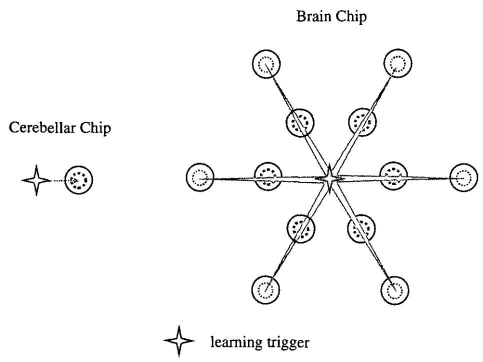


A: McCulloch-Pitt's neuron
Learning trigger is explicitely added to parallel it with cerebellar chip shown in B.

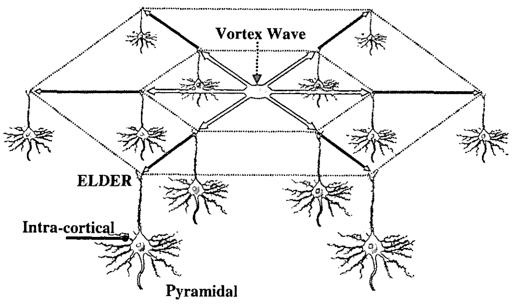
$$y(t+1)=\begin{cases}1 & if \quad \sum_i w_i x_i(t) \geq \theta \\ 0 & if \quad \sum_i w_i x_i(t) < \theta\end{cases}$$



B: Cerebellar Chip
Purkinje cell behaves like McCulloch-Pitts' neuron. Inputs from parellel fibers (PF) reaches the dendrites of Purkinje cell and forms synapses which efficacy is modifiable (plasticity). Input from climbing fiber (CF), which carries "error signals", activates Purkinje cell in one to one fashion and plays the role of learning trigger.



C: Conceptual differences between cerebellar and brain chips
While, in the cerebellar chip, climbing fibers urge a single Purkinje cell's learning in a one to one fashion, in the brain chip, the trigger structure (Climbing fiber Equivalent Organon, CEO) urges multiple pyramidal cells simultaneously. In this sense, the brain chip is the two dimensional version of the cerebellar chip which has a one dimensional design.



D: Brain Chip
The brain chip represents a biological Kohonen's map.

Implication for Society

The fact that brain function is a complex system which self-organizes based on initial and boundary conditions implies that the mind is formed by interactions with the environment in which an individual happened to be placed.

The brain is a biological substrate that specializes as a highly sophisticated machine dealing with information. This duality of the brain, as does its interaction with the environment, introduces further complexity when one considers its functionality. Functionality that is strongly influenced by the biological brain is more affected by the physical environment, whereas functionality that is strongly influenced by network connectivity is more affected by the informational environment.

The physical brain obeys the principle of homeostasis and its adaptability is limited and slow. By contrast, connectivity of the brain is in principle plastic and possesses the inherent capability of rapid adaptation. As far as it remains within acceptable range, environmental changes provide proper driving forces for species progression. However, beyond the range, such changes result in destruction.

The human brain is known to have the property of "critical time" defining the basic rule how the brain is utilized. More than ever in mankind's history, individuals exhibit apparent difficulties in dealing with information overload. The typical behavior is characterized by lack of proper engagement of the prefrontal lobe. Intriguingly, this is also the condition observed in schizophrenia.

Implication for Clinical Medicine

On August 28th, 2001, the New York Times featured an article on modern rehabilitation medicine, and included an interesting report on the work of my old friend, Dr. Paul Bach-y-Rita.

Since the time we worked together at the University of California, Davis, Dr. Bach-y-Rita had been making serious effort to develop a method to provide "sight" to blind people. His first trial was to deliver visual information obtained from a CCD camera through a needle sheet attached to the skin. This method is generally called sensory substitution. His first attempt produced only limited success. Critics maintained that the brain processes visual information and tactile information independently and, therefore, his method would never produce practical results. However, the clinician in Dr. Bach-y-Rita convinced him the brain to be highly plastic and he continued to search for more sensitive means.

The article in the New York Times reported that Dr. Bach-y-Rita produced dramatic results by delivering visual information to the tongue. After proper training, blind people were able to distinguish human faces and even hit a moving ball with a bat. He demonstrated that under certain conditions an individual can see using through the tongue.

The fact that brain function is a complex system which self-organizes based on initial and boundary conditions implies that the usage of the brain is not tightly determined at birth. Identical functionality can be created through many different ways dependent on what kinds of conditions the brain faces. The blind rehabilitation cases shown by Dr. Bacy-y-Rita convincingly demonstrated this fact.

A new era of rehabilitation medicine is definitely emerging. It is up to the given individual whether or not he can free his mind from the constraints of old concepts.

Further Reading

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