Computer and Mind

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The human brain is often called a computer and several electronic devices commonly used in information technology (IT) like computers, neural networks, artificial intelligence equipments and robots, are believed to be modeled on the basis of our understanding of the brain. It is also true that in recent years these artifacts have been invaluable in exploring and understanding the structure and function of the brain. And though some feature of the implements used in IT may mimic the brain, the two have no more than superficial similarities. Intense activity in both these fields, each likely to benefit from the other, is probably the reason for Prof. Menon to includ me in this symposium.

In view of the diverse background of the participants of this symposium, it may be desirable to provide a brief outline of the structure and function of the brain prior to discussing its information processing function which no doubt represents a vital but only one of its diverse attributes.

The Brain: Anatomical Organization

The brain of an adult human being weighs approximately 1300-1500 grams. It is enclosed in a rigid skull. Grossly it is divided into three major components —largest being the **Cerebrum,** consisting of two cerebral hemispheres inter-connected to each other. The **Cerebellum,** much smaller and situated below the cerebrum, has a distinct appearance and functions of its own. Situated in the centre of the brain, connecting the cerebrum and the cerebellum and extending outside the skull as the spinal cord, is the **Brain Stem** or the central core. Each one of these is further sub-divided into well defined components. The brain receives its information from the world around us and our own body through its *sensory nerves* subserving the five major senses, viz. *vision, hearing, smell, touch* and *somesthetic sensations (touch, pain, muscle-joint sense).* Sensations from its *visceral organs,* e.g. *heart, lung, intestines, urinary bladder,* etc. are communicated by the autonomic nervous system. Brain executes its motor functions through its motor nerves and pathways.

The basic building blocks of the brain are the nerve cells (neurons) with their processes (axon and dendrites) and the supporting cells (the glia).

Neurons are arranged in well organized columns covering the surface of the cerebrum and the cerebellum and constitute the so-called grey matter or the cortex. In addition they are seen as tightly packed clusters in the depth of the brain as distinct nuclei and structures like the *Thalamus, Hypothalamus, Striatum, Amygdala,* etc. often collectively referred to as the Basal **Ganglia.** Out of the approximately 30 billion neurons in the brain, the cerebral cortex contains around 10 billion. To accommodate so many cells the cortex is folded to provide the characteristic appearance of the **gyri** and **suici**. The cerebral cortex with its supporting elements makes up approximately 80 percent of the brain's total volume. It is actually a recent development in the course of evolution. While a tripling of brain size from 400 to 1300 grams marks hominid brain evolution, the brain of Homo Sapiens has hardly changed in size, form or external morphology since the species first appeared less than a hundred thousand years ago (Mountcastle 1998). While the brain of the rodent or monkey has many structures identical to human brain, the latter is not a scaled up model of the former.

From the multi-potent progenitor cells, a well orchestrated process of development results in the migration of the specialized neurons to their final destination in precisely organized columnar modules which characterize the cerebral cortex. Simultaneously these neurons develop precise connections with their genetically determined targets which ultimately produce specific functional units. Each group is connected to only certain subsets of other groups to subserve specific functions, e.g. vision, smell, somesthetic sensation, voluntary movement, etc. These distinct cortical areas are known to be discrete cytoarchitecturally as described by Broadman and manifest a somatotopical (point to point) representation of the sensory and motor functions as revealed by Penfield Mountcastle (1986), Hubel and Wiesel (1963). The organization of the functional areas has been elaborated not only to particular region of the cortex but to the level of the individual cells within the columns playing a specific role. Thus at its higher level of anatomical organization it appears that the cortex is nicely divided into areas, regions and specialized parts that, in general, are functionally segregated or specialized. We can trace the sensory pathways from the **peripheral endorgan** (sensor) in the *skin, retina, cochlea, nasal mucosa, tongue,* etc. to specific and discrete regions of the brain, even specific columns or cells. Similarly we can trace the motor pathways from discrete regions of the cerebral cortex to the specific motor neurons in the spinal cord and onwards to their target muscles.

Each neuron has a cell body (the soma) and multiple processes to receive (the dendrites) and send messages (a single axon). The neuronal processes of one neuron in turn communicate with others not through physical contact but at a junction called the **Synapse** which is a membrane bound cleft. On an average each neuron is connected to about one thousand other neurons. Some neurons are reported to have as many as 20, 000 synapses. It is estimated that there are nearly one to ten trillion synapses. The neuronal process carrying a message to the synapse is called **Presynaptic** and the one receiving it is called **Postsynaptic.**

Over the years it has become evident that the organization of local micro-circuits, their connectivity to other cortical and subcortical structures is far more complex than so far believed. Many cognitive functions previously thought to be localized to a single cortical area have been shown to engage many and frequently widely separated areas of the cortex in a distributed rather than hierarchical arrangement. It is now established that in the case of vision there are as many as three dozen (or probably more) different areas in the monkey brain, each contributing to function for example, the detection of line orientation, the movement of objects, the colour, etc. widely distributed in the occipital, parietal and temporal lobes. These functionally different segregated areas are no doubt reciprocally connected. The same is true for other functions as well. Thus brain activation related to voluntary movement has been found in at least fourteen areas, including the primary motor area (Frackowiak: 1998). This is in contrast to the three, primary, secondary and supplementary areas, identified by Penfield nearly fifty years ago, on the basis of mild electrical stimulation of the cortex of conscious human subjects during operations for *epilepsy*.

Before one gets the impression that all functional units in the brain are hard-wired as in a computer, it must be emphasized that at the synaptic level there is a remarkable degree of plasticity. Earlier believed to be a feature of early developmental stage of the brain, it is now unequivocally established that synaptic plasticity and modifiability are virtually universal properties of brains at all ages. No two brains are identical, not even those of the identical twins, at the finest level of micro circuitry. Neither is the same brain microstructure identical from moment to moment. Depending upon the environmental inputs and specific functional requirements at a given moment new synaptic connections are made and some existing ones, dismantled. This led Gerald Edelonan to comment that "Brain is 'special', that it is a gross mistake to think of it as an ordinary 'machine'. Each brain has uniquely marked in it the consequence of a developmental history and an experiential history". This plasticity of the neuronal circuitry would no doubt be a nightmare for anyone wanting to develop an artificial brain model.

Physiological Organization

A message generated or transmitted by a neuron travels along its axon as an action potential till it reaches a synapse, where through a cascade of chemical events it is passed on to the other neuron/neurons. Synaptic transmission depends upon the release of a transmitter substance from the presynaptic terminal into the synaptic cleft. This in turn modifies the membrane of the postsynaptic (recipient) membrane involving a variety of receptors, ion-channels, transporters and other molecules. More than fifty neurotransmitters have now been identified in our brain. In addition there are a host of other neuropeptides and hormones which are involved in the generation, propagation, transmission and modification of the electrical signals which form the basis of interneuronal communication. These diverse neurotransmitting molecules may exert strikingly different effects on the firing state of their target neurons. Moreover, the same neuron may synthesize and liberate upto ten chemical messengers. The diversity of chemical coding accessible to nerve cells is thus very large and complex (Changeux 1998). The electrochemical repertoire involved in "cross talk" between the neurons is thus not only rich but subtle. Nothing like this has so far been attempted in any man made machine. This is one of the many ways in which the brain differs from any computer so far developed.

The brain operates in terms of interactive groups of neurons, whose rate of firing excited, inhibited or modified as a consequence of coded information, transmitted to it either from a peripheral sensor or from another set of neurons within the neurons system. The resulting electrical activity at different levels of functional organization varies from millisecond to seconds. Thus an action potential, the basic unit of electrical signal across a synapse lasts a few milliseconds; an evoked potential, an expression of integrated electrical activity from a specific region of the cerebral cortex in response to a sensory stimulus, is measured in hundreds of milliseconds. The readiness potential that precedes voluntary motor activity and recorded with **electro encephalography (EEC)** may last seconds. These constitute the temporal component of any spatial functional organization (Frackowiak 1998). Recent experimental studies suggest that the brain encodes information, not just in the firing rates of individual neurons, but also in the patterns in which groups of neurons work together (Brinaga 1998). Thus the repeated demonstration of consistent patterns of local brain activation during defined sensory, motor or cognitive activity now provide objective evidence of functional organization which can be measured non-invasively with the help of modern brain imaging techniques. As a result , it has now been possible to map even some of the mental activities, thought, memory, emotion on to specific regions of the brain (Hymann 1998, Morris et al 1998).

It must be realized that the brain does not function as a simple input- output system. Not only are the interconnections between the individual neurons and groups of neurons, between one functional unit and the other extremely complex but non-linear. Practically at every level of its functional organization there are feedback loops which are capable of modifying or even blocking the input. Various functional units even in a single functional system, e.g. vision or hearing are not in continuity or even contiguity but widely distributed. The grossly hard wired systems under genetic control (nature) are plastic and modifiable under influences of environment (nurture). While most of this plasticity resides at the level of synapses, recent evidence reveals that it may involve other structures, e.g. spines on the dendrites, change in circuitry, new circuit formation and even neurogenesis (new neuron formation) (Kempermann and Gage 1999). Most functional units exhibit a great deal of redundancy. The system is endowed with the ability of selecting signal from noise at various levels of organization, and categorizing patterns out of a multiplicity of signals (see later). It has the ability to learn, memorize, recall and even create novel outputs thus endowing it with qualities of creativity and intuition. Functioning as an integrated system, not just isolated units, it has the capability of abstracting individual elements of an input (say vision), distributing these to different sets of specific neurons (concerned with shape, size, colour, movement) for storing these, for future recall and when required, reconstituting these to the original composite image. Integration results jointly from the patterns of connectivity and the dynamic properties of the interacting neurons. This is specially so in respect to the cognitive functions, earlier thought to be localized to a single cortical area, but now shown to engage many and frequently widely separated areas of the cortex (Mount Castle 1998).

Information Processing

Based on the knowledge of the structural and functional organization described above, it is now possible to have a better understanding of the information processing function of the brain.

Utilizing this paradigm one may look at the example of vision, one of the most thoroughly investigated systems. A basic organizing principle of the visual system (and to a great extent other sensory systems) is that a relatively large number of specialized cells at each stage supply information to a smaller number of cells at the next stage, which in, turn have their own specialized function. Upto a certain stage of organization the system functions in a hierarchical fashion but ultimately it becomes a distributed system *(Figure 2)*. Thus any visual stimulus would pass through the retinal ganglion cells (the rods and cones), along their axons (in the optic nerve) spatially reorganized in the optic chiasma, carried to specific layers of neurons in the lateral geniculate body (a part of the thalamus, the principal sensory ganglion) to be projected to the primary visual cortex (VI) in the occipital lobe, reflecting a precise spatial representation of the visual field and further distributed to other visual areas —V2, 3, 4 . . . for processing information related to location, visual form, colour, orientation and motion of the object. It must be appreciated that unlike a laboratory experiment where these visual signals can be studied with minimal or no distraction or intermingling with other sensory inputs, in day to day life these are embedded in diverse stimuli emanating from the environment outside and individual's own body. Hence the information generated by a visual stimulus (and for that matter any sensory stimulus) would be of necessity integrated and coordinated with a flood of information impinging on one's consciousness. Much of the information would require to be blocked or eliminated at various stages of information transmission, analysis and storage . On the other hand, there are some inputs which require special attention, prompt voluntary response or imprinting in memory for future needs. It is obvious that in addition to the neural circuitry that serves the five primary senses, the human brain has numerous other systems for making sense of external stimuli and regulating the body's ability to function in the world (Ackerman 1992). A large amount of information has accumulated in recent years about the mechanisms involved in information processing of individual sensory/motor functions but very little is known as to how these are integrated as a unified perceptual experience or volitional activity which are the essence of human behaviour. There is much speculation on this subject, some comparing it to a giant computer engaged in a complex computation and others believing it to be in the nature of alterations in the ongoing intrinsic electrical oscillations resulting from thalamus-cortical reverberating projections. However, it must be recognized that this aspect of information processing in the brain remains an area of ignorance. This has recently been succinctly summarized by Vernon Mount Castle , an ardent investigator of this subject thus: "Many functions attributed to cerebral cortex like thresholding, amplification, feature convergence and new feature construction, distribution, coincidence, detection, synchronization , long term storage and retrieval, etc. are not yet fully understood at the level of neuronal circuit operation" (Mount Castle 1998).

Information storage or Memory

Utilizing a host of new technologies, including EEG and event related potential (ERP), functional magnetic resonance imaging (fMRI) and magnetoencephalography (MEG), Positron emission tomography (PET) and supplementing these with biochemical and molecular investigations in cell cultures, brain slices, laboratory animals and more recently conscious, cooperative human volunteers performing learning and memory tasks, unprecedented information has been gathered regarding the neuronal, neurochemical, molecular and biophysical substrates of memory. The formation of memory not only involves multiple anatomical regions but a complex set of cellular events, involving a variety of neurotransmitters, second messenger pathways, post-translation modification of protein in the cytoplasm and regulation of gene expression in the nucleus. It would be impossible to even summarize this vast knowledge in this brief review. However, a few salient features are mentioned.

Memory entails sensory perception, encoding storage, consolidation, stabilization and retrieval. The earlier prevailing concept that memory is a single entity that could be traced to a single structure or location has proved to be false. There is enough evidence to suggest that memory consists of multiple components subserved by many different regions of the brain based upon a distributed network of neurons. Thus the neural substrate of elements like short term or working memory and long term memory or episodic or semantic memory; explicit, implicit or associative memory, have been localized to diverse regions of the brain, including the prefrontal cortex, the temporal cortex and hippocampus, the limbic system, medial and rostral part of the thalamus, fornix and mammalary bodies, dorsal mesencephalon and cerebellum (Thompson 1986, Flackowiak 1990, Goldman Rakie 1992, Cabrieli et al 1997, Wickelgren 1997,Ungerleider 1995).

Let us take the example of working memory which is a part of the so-called short term memory and operates over a few seconds. A combination of moment -to-moment awareness and instant retrieval of archived information constitutes "Working memory". Like an erasable blackboard it allows us to hold briefly in our mind information—whether it be words, numbers, figures or a map of our surroundings—essential for comprehensive reason and planning (Wickelgren 1997).

Micro-electrode recording from individual neurons in the prefrontal cortex revealed that some cells showed heightened electrical activity when information was presented, whereas others became active when the animal was recalling the information. A third set of neurons responded most strongly when the animals began their motor response. Goldman Rakie (1992) thus postulates that prefrontal cortex functions as an intermediate between memory and action. Furthermore, the prefrontal cortex, with its elaborate network of reciprocal connections with major sensory, limbic and pre-motor areas of the cerebral cortex, is dedicated to spatial information processing. She believed that the prefrontal cortex is divided into multiple memory domains, each specialized for encoding a different type of information such as the location of objects, the features of objects (color, size, shape) and in humans semantic and mathematical knowledge. Dopamine is considered to be one of the most important chemicals implicated in the cognitive process which subserves working memory. On the other hand on the basis of neuroimaging data Fletcher and Rugg (1997) demonstrated that effective encoding in episodic memory was associated with enhanced activity in left prefrontal cortex, whereas retrieval was accompanied by the enhancement of predominantly right side prefrontal activity. Thus the prefrontal cortex appears to be essential for working-memory duties, holding the relevant information on-line performing complex processing functions, as well as for planning and attention. However, this is not the only site for working memory nor the primary site for long term memory.

It has long been known that the hippocampus and the surrounding temporal lobe structures are involved in memory functions. Bilateral hippocampal lesions in man result in amnesia (Milner 1958, Scoville and Correll 1973). It is interesting to note that such lesions improve the capacity to record the daily current conscious experience without any disturbance of reasoning, attention or concentration. Gentle electrical stimulation in epileptic patients reactivated the past record of the "stream of consciousness" (Penfield and Perot 1963). Functional brain imaging in humans provides unambiguous demonstration that the medial temporal lobe is active at the time of verbal memory retrieval (Nyberg et al 1996, Haxby 1996). Gabrieli et al (1997) observed that encoding tasks yielded increased signals for unfamiliar information in a posterior medial temporal region (parahippocampal cortex). On the other hand retrieval tasks yielded increased signals for successfully remembered information in an anterior medial-temporal region (subiculum). These results indicate that separate components of the human medial temporal-lobe memory system are active during distinct memory processes. Such information regarding the precise role the other regions of the brain play in memory function is rapidly accumulating but will not be discussed here any further.

As mentioned earlier, synapses play a pivotal role in neuronal communication, information transmission and probably also in information storage. It is now generally accepted that long-lasting activity - dependent changes in synaptic strength as observed in case of **long term potentiation** (LTP) are of fundamental importance for the development of neuronal circuitry and for information storage in mammalian brain (Nicolland Malenka 1995). Sensory experiences leave their imprint on the brain by altering the effectiveness of synapses between neurons. Based on the strength of the stimulus some synapses on a neuron grow stronger and others grow weaker and the pattern of synaptic change represents a memory of experience; consolidation requires protein synthesis, which makes the temporary changes permanent(Bear 1997). However, it must be emphasised that synaptic change though essential is not identical to memory. Amongst the various hypotheses the one currently finding favour is that memory results from the selective matching that occurs between ongoing neural activity in a particular region and the signals from the world, the body and the brain itself. Signals from the world or other parts of the brain act to select particular circuits from the myriads of circuits available in a given brain area. The synaptic alterations that ensue affect the future responses of the brain to similar or different signals. Thus in this view, a memory is dynamically generated from the activity of certain selected subsets of circuits (Edelman 1998). Reverberating thalamus cortical circuits seem to play a significant role in this process. There are other hypotheses too, but for the present there is a need for more empirical data and modeling studies to fully understand the process.

The above account may suggest the

brain to be a modular system comprised of regions, areas, circuits or even individual neurons dedicated to specific functions organized in a hierarchical fashion. This picture no doubt emerges as a consequence of the reductionist approach commonly used in investigating complex systems. However, recent empirical evidence, specially based on modem brain mapping techniques reveals parallel, distributed and interactive processing, coding through neuronal assemblies that are not specialized for only one type of information, and existence of non-hierarchical and non-modular processing. It is this type of organization that provides for the dynamic holistic aspect of many of the higher mental functions. Thus Edelman (1998) has suggested a comprehensive view of effective brain function to arise both from the combined action of local segregated parts having different functions and from the global integration of these parts mediated by what he calls the process of re-entry.

In summary, today we have a great deal of knowledge about the individual neurons and the way they connect to each other to form functional units. A large number of neurochemicals they use to communicate with each other have been identified The molecular events associated with neural communication have been unraveled. However, we still do not fully understand how this neural machinery is integrated to subserve higher mental activity.

Brain and Computer

In a symposium on Information Technology an account of brain structure and function would be incomplete without referring to the significance each has for the future understanding and development of both these fields. It would be generally accepted that the human brain is enormously more complex than any electronic computer at present. The plastic microcircuitry of the brain, capable of responding to the inputs from the environment and needs of the ever changing repertoire of behavioural responses (output) is vastly different from the hard wired architecture and virtually preprogrammed outputs of a computer. While the brain predominantly depends on distributed parallel computing, most computers utilise serial processing. In contrast to the neurons in the brain which can take on any one of the series of values over a continuum, the transistors in digital circuits function on a limited 0 or 1 response. The ability of the brain microcircuitry to both structural and functional plasticity and use of diverse chemicals to do so is undoubtedly its most complex characteristic.

In some respect the existing generation of computers are "superior" to human brain. Their capabilities to carry out massive and complex calculations at speeds greatly faster and more precise is one of these. The computers can also have remarkable "memory". Scientists have already developed or are on the verge of developing computers that can learn for themselves, generalize from particular examples, draw particular examples from general principles or even evolve new solutions to problems they have never faced, including playing chess as good as, if not better, than the best living player. However, it is true to say that so far the computers man has invented are something quite different from the brain. No doubt current developments in Neurosciences on the one hand and those in Computer Science (including Artificial Intelligence and Neural Networks) on the other have benefited both in many ways. As a consequence whole new Fields of Computational Neuroscience on the one hand and Neuroinformatics on the other, have emerged. However, as Francis Crick (1984) concluded, the hope of understanding the properties of the brain with the help of computer algorithms from neural networks has not materialized. No doubt, there are great optimists like Ereck D. Solla Price of Yale University who "expect computerized artificial intelligence to team up with the human brain to change the very pattern of human thought" . So as of today we have a long way to go to fully understand or artificially model and recreate even simple functions like sensing the nuances of environmental inputs or mimicking the smooth and graceful activities so effortlessly carried out even by a toddler, leave aside an accomplished pianist or a Kathak dancer. The mechanisms underlying our thoughts, emotions, creative urges, leave aside solving the riddle of brain- mind relationship, remain unresolved. Nevertheless there is hope that with closer interaction between neuroscience and information science the path to this understanding will become easier and more rewarding.