The Hidden Brain

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"If the human brain were so simple that we could understand it, we would be so simple that we couldn't."

- *Emerson M. Pugh in "The Biological Origin of Human Values"*

The human brain is an incredibly complex and awesome apparatus with its multitudes of folds and overlapping structures. It has tremendous power to gather and process all sensory data and take appropriate decisions. Brain is an excellent miniature system that is capable of the most sublime thoughts while requiring very little power to function, thanks to its highly sophisticated molecular and cellular architecture which is a marvel of evolution. With billions of intricate neural connections squeezed within its small volume, the brain is often compared to a gigantic telephone network, a computer or the internet, but all these analogies are inappropriate and do not capture the brain's complexities. The brain has a superbly efficient neural network –it is, in fact, a learning machine where memory and thoughts are distributed throughout its volume rather than being concentrated in a central area like the CPU of a computer. It does not even compute very fast, but it learns amazingly efficiently – many times more efficiently than the most powerful supercomputers of our day. It learns new tasks astronomically fast, and can learn even from its mistakes. But its immense complexity becomes simpler to grasp if we consider the evolutionary processes that created such an incredibly complex and efficient leaning machine.

An average human brain contains about 100 billion nerve cells or neurons[1] packed within a volume of about 1300-1400 cc. within the skull. The brain is the major component of our central nervous system and weighs about 1.4 kgs. The brain has three main parts, the cerebrum, the cerebellum and the brain stem. The cerebrum or the forebrain alone takes up 75% of the brain size and accounts for 85% of its total weight. It is divided by a large groove, known as the longitudinal fissure, into two distinct hemispheres: the left and the right[2], which are linked by a large bundle of nerve fibres called the corpus callosum, and also by other smaller connections called commissures, through which the two hemispheres communicate with each other. The two hemispheres look similar, but differ slightly in structure and functions, each being divided into four cortical areas called lobes -frontal, temporal, parietal and occipital. These lobes and most of the important elements within them are split into symmetrical pairs in the left and right hemispheres.

The cerebrum is enveloped by a sheet of neural tissues known as the cerebral cortex which constitutes the "grey matter" of the brain, white the inner "white matter" is composed of bundles of nerve cell projections called axons, which cover no less than 170,000 km and connect the grey matter areas of the brain to each other, carrying nerve impulses between the neurons. About 90% of all the neurons in the brain are located in the cerebral cortex itself, supported by about four to five times as many glial cells,

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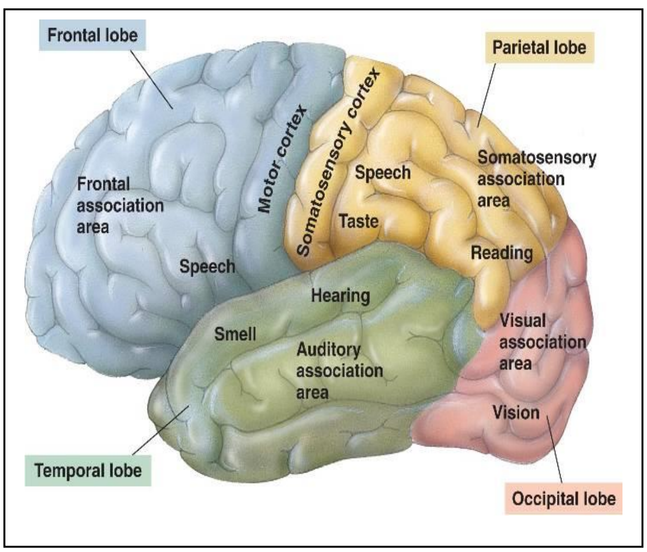
[1] The terms neuron and synapse were coined by the British neuroscientist Charles Scott Sherrington (1857-1952).
[2] The "left" and "right" refer to the owner's point of view, not an outside viewer's.

which are fatty cells that provide insulation to neurons and deliver nutrients to them, and produce a fatty white substance called myelin to coat the axons. The cerebral cortex itself is only 2 - 4 mm thick, and contains six distinct but interconnected layers grooved and folded into the characteristic convoluted patterns called gyri, allowing a large surface area (typically 2500 square centimeters) to be packed into the small volume inside a skull. Each gyrus is separated from its neighbour by a furrow called a sulcus, and more than two-thirds of the cerebral cortex is buried in the sulci. The largest part of the cerebral cortex, the outer layer of the brain, is the neocortex, neo meaning new to indicate that this is the newest part of the brain to evolve. As we shall see, it plays a key role in cognition and consciousness. The neocortex is made up of six layers, labelled from the outermost inwards, I to VI. The other part of the brain called the allocortex is again divided into two parts: the archiocortex and the paleocortex. Allocortex is responsible for homeostasis - our regular physiological processes as well as our instinct for self-preservation (and hence the preservation of the species).

Within each cerebral hemisphere, the frontal lobes are located inside the forehead at the front of the brain. This area controls all higher functions of the brain, planning, personality, memory, language, problem solving and complex decision making. Frontal lobe contains a motor cortex that controls the motor functions i.e. movement of the body's voluntary muscles by sending commands to the peripheral nervous system. Frontal lobe possibly played a key role in our bipedalism, the essential human function. Our upright posture may not have been possible before the development of the frontal lobe. An area called the Broca's area which controls the production of speech is also located within the frontal lobe. The front part of the frontal lobe is known as the prefrontal lobe and is believed to be associated with many of our higher cognitive behaviours like planning ad decision-making. Damage to the prefrontal lobe results in the person losing the essential attributes that make us human – ambition, empathy, foresight, morality, social life and sense of dignity, while retaining all other cognitive abilities intact. For this reason, this area is often referred to as the 'seat of humanity'.

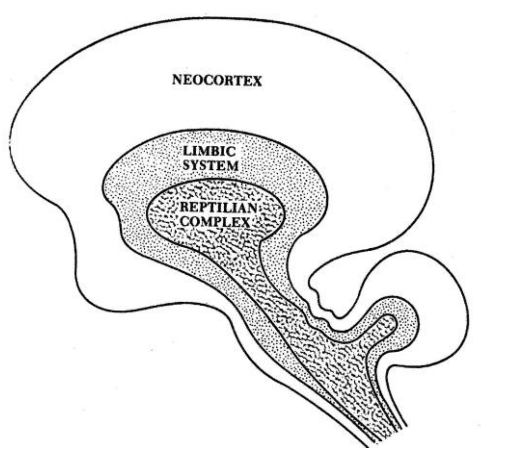


Areas of the brain mapped to different human activities

The temporal lobes which are located just behind the temples of the head contain the primary auditory cortex and the auditory association area. The left temporal lobe also contains the Wernicke's area involved with the comprehension of language. The parietal lobes lie at the top and back of the brain and house the somatosensory cortex that processes the sensory signals from different parts of the body, cells at the top receiving information from the bottom of the body and so on. In particular it is responsible for the sensation of touch, pain and temperature, spatial perception, and distinction of size, shape or colour.

Parietal lobe is also involved with symbols – a lesion in the angular gyrus[3] within the parietal lobe causes alexia, or inability to recognize the printed word. Angular gyrus is the area where cross-sensory synthesis takes place. The occipital lobes lie at the back of the brain at the base of the cortex and process the visual information from the eyes in the primary visual cortex and the visual association area.

Broca's and Wernicke's areas together with the pathway between them called *arcuate fasciculus* which is actually a bundle of axons primarily control our ability to use language, even though language may be distributed in other areas as well, just as these areas may be used for other brain functions also. We know this from the examination of patients in whose brains these areas somehow got damaged, say by a stroke, leading to a condition known as *aphasia*. In Wernicke's aphasia, also called fluent aphasia, a person has the ability to speak fluently using grammatically correct sentences just like any other normal individual, except that nothing that he says makes any sense at all. They can produce sound and speech that has no meaning. Broca's aphasia is almost the complete opposite of Wernicke's aphasia - here the speakers cannot speak fluently, but whatever they speak is meaningful. They have problem is speaking but not in understanding, because their Wernicke's areas are intact. Some the pathway accurate fasciculus can also be damaged, in which case patients can speak fluently about things that make perfect sense, but lose their ability to repeat words or sentences they have spoken, or to recollect something from memory.[4]



A schematic representation of the Triune Brain Model of Dr. Paul MacLean

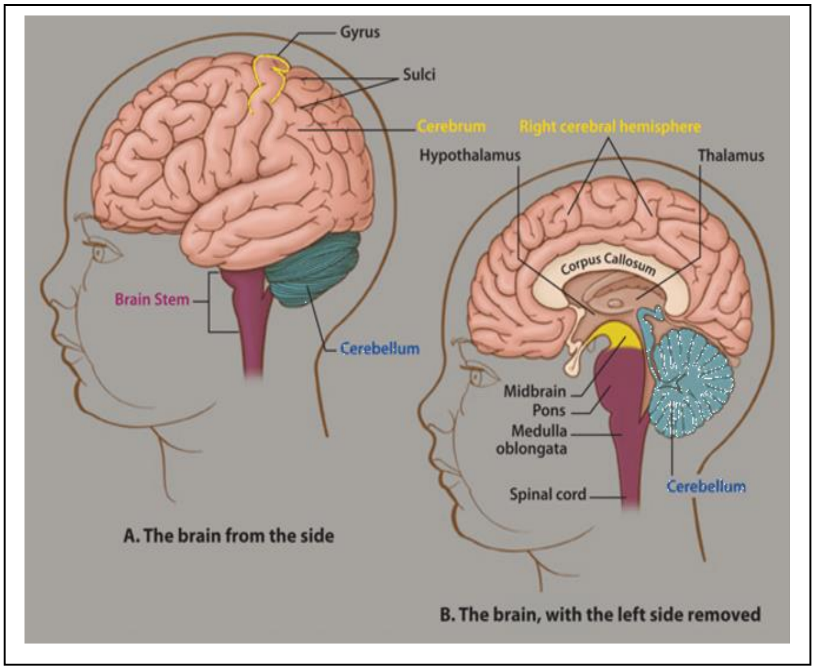
A model for understanding the brain in terms of its evolutionary history is the famous Triune Brain Theory developed by Dr. Paul MacLean of the National Institute of Mental Health, USA in the early 1970s based on his experiments with the squirrel monkeys.[5] According to this theory, three distinct brains emerged successively in the course of evolution that now co-inhabit the human skull. First of these is the reptilian brain, also known as the reptilian complex or the R-complex which surrounds our midbrain. This is the oldest of the three and controls body's vital life-sustaining functions such as heart rate, breathing, temperature and balance. We share it with all reptiles and mammals.

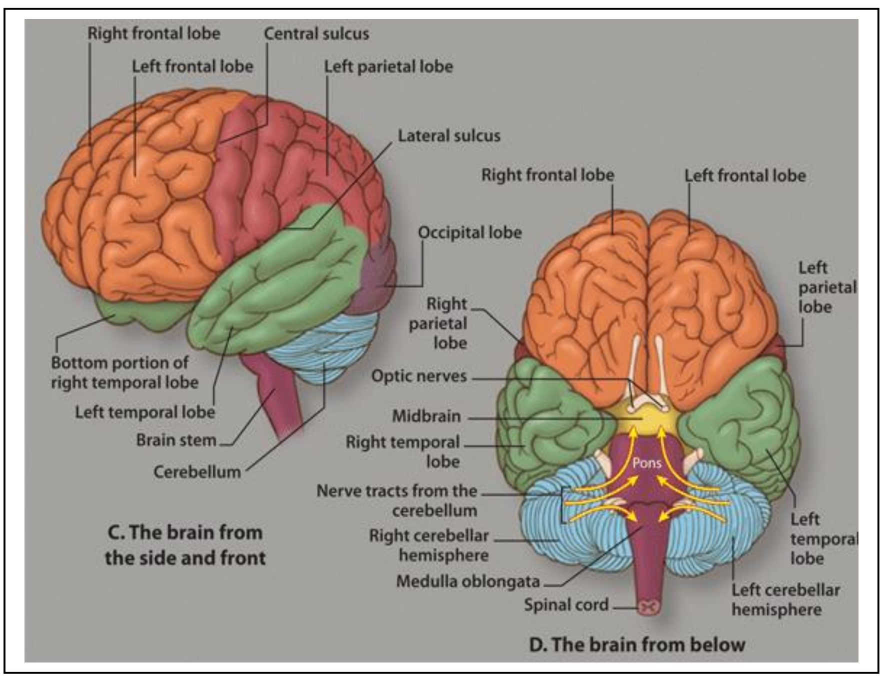
[3] A *gyrus* is any of the surface convolutions or rounded ridges that are packed along the cerebral hemispheres of the brain. Each gyrus is separated from its neighbor by a furrow called a sulcus.

[4] Evidence is now emerging that damage in the neural circuits that link the cortex with other parts of the human brain as well as in basal ganglia, thalamus or other sub-cortical structures or pathways connecting these structure may also cause aphasia.

[5] Source of Schematic Diagram: Sagan, Carl, *The Dragon's of Eden*, Ballantine Books, New York, 1977, 59

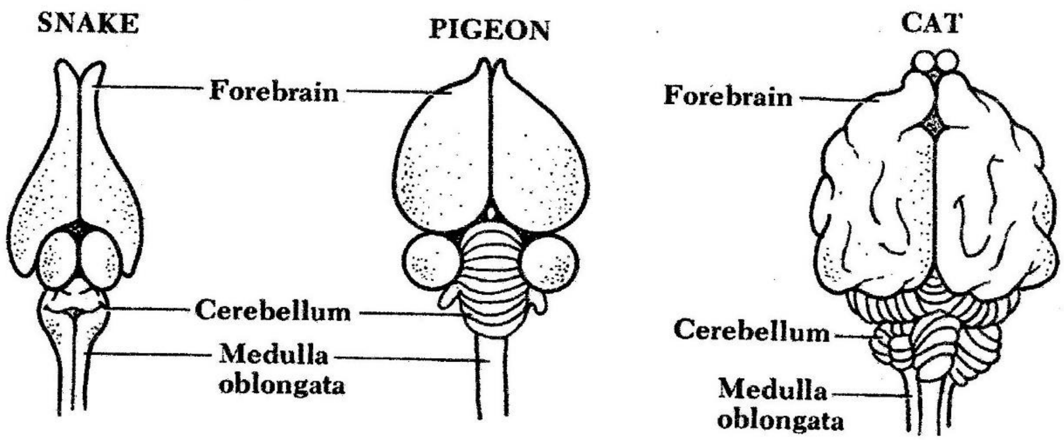
The earliest structure of the brain to evolve several hundred million years ago was the brain stem and cerebellum (meaning 'little brain'). Brain stem is an extension of the spinal cord that contains the Medulla Oblongata which regulates breathing and heartbeats, and the Pons ('bridge') that provide the pathways for sensory and motor impulses to and from the cerebral hemispheres. The cerebellum plays a prominent part in coordinating our muscular movements, neuromuscular control and our reflexes - all its functions are unconscious, involuntary and automatic.



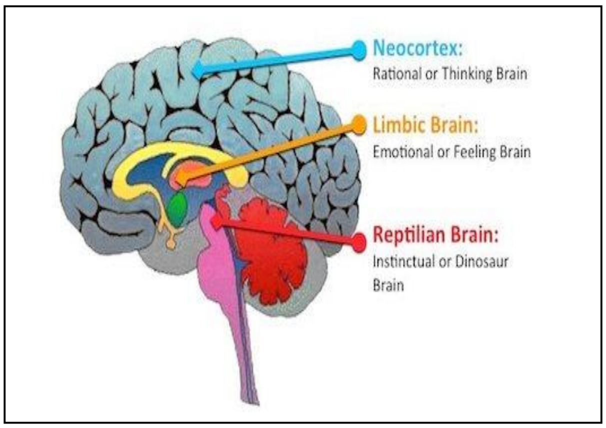


It was in 1970 that Dr MacLean first noticed that the cerebellum, the brain stem and the basal ganglia[6] that together constitute the back and centre part of our brain are almost identical to the brain of reptiles. The Reptilian Complex is essential for our survival; it regulates our eating, digestion, heartbeat, sleeping, sexual behavior, reproduction and the 'fight or flight' instinct. This is the oldest structure in the brain that can be traced back to about 500 million years. Reptiles and amphibians have a cerebrum that works very similar to the R-Complex, which is the signature evolution has left within our brain from the time mammals were evolving from reptiles and amphibians.

[6] Basal ganglia lies deep inside the cerebrum and controls our automatic motor movements, posture, cognition and facial expressions. Any damage to it would result in inability to control our voluntary muscle movements.



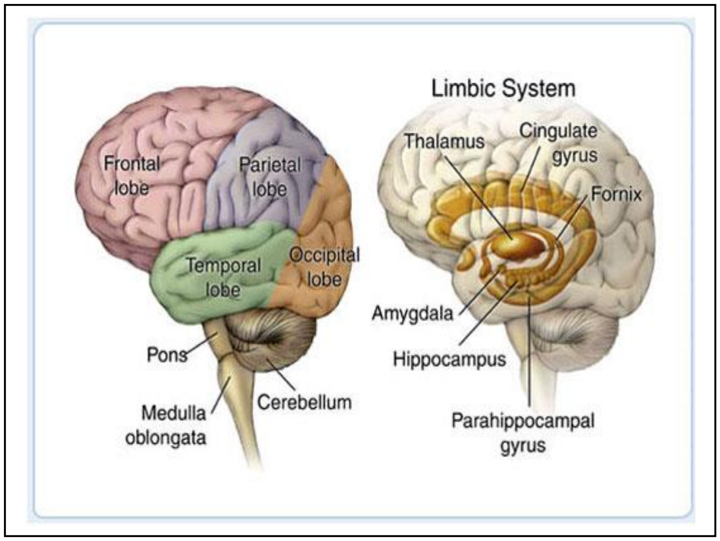
Schematic diagram of the Brains of Reptile, Bird and Mammal. Cerebellum and Medula Oblongata are parts of the hindbrain[7]



As reptiles evolved into mammals, the brain necessarily increased in size and complexity as new structures evolved to control and coordinate the increased complexities and activities of mammalian life. The mammalian brain is similar to the limbic system that lies within the neo-cortex, in the centre of the brain surrounding parts of the reptilian brain and is prominent among animals that live in social groups like the apes. These social groups with their complex dynamics of behavior would need a sophisticated limbic system to distinguish between potential enemies, allies and rivals. The limbic brain which emerged in the first mammals about one hundred and fifty million years ago is capable of storing memories of behaviours that produced pleasant and unpleasant experiences, and is thus responsible for emotions in human beings. It is the seat of our value judgments which influences our behavior, often unconsciously. In the paleo-cortex and limbic system, the brain has indeed preserved the memories of our evolution from reptiles and mammals, as shown in the picture alongside of the Triune Brain. These three parts of the brain do not operate independently, but have numerous neural interconnections through which they interact. The neural pathways from the limbic system to the cortex are especially well developed. We share the limbic system with other mammals though not fully with the reptiles.

[7] Sagan, Carl, *The Dragons of Eden*, Ballantine, 1978, 55.

The main structures of the limbic brain shown in the picture alongside are the hippocampus, the amygdala, and the hypothalamus. Within each hemisphere of brain is located a thalamus that relays the incoming sensory signals to appropriate areas of the brain for processing. Below it lies the hypothalamus, which controls hunger, thirst, the circadian rhythm, anger, pleasure and emotions. The largest structure of the limbic system is the hippocampus which plays a large role in processing our short term memories into long term memory. The amygdala controls our fear and aggression, and is also involved in emotion and memory. Electrical stimulation of the amygdala in animals causes extreme fear or frenzy. It is believed that altruistic behavior originated in the limbic system. Mammals and birds are the only living beings that harbor and display affection towards their young offspring and care for them. The relatively larger capacity for information processing among the mammalian brains owes its roots to this distinction. As Carl Sagan observed, “Love seems to be an invention of the mammals.” The pituitary gland, the pea-sized gland known as the ‘master gland’ which dominates the human endocrine system and controls the growth, development and functioning of all other endocrine glands, is an essential part of the limbic system. The olfactory cortex related to smell is among the oldest parts of the limbic system, and played the most vital part in evolutionary progression of mammals, in identifying food, predators, (also preys), mates and in sexual behaviour.



Finally, we have the third layer of the brain in the cerebral cortex, the outermost layer of the brain with its two large cerebral hemispheres, which is responsible for the development of human language, abstract thought, imagination and consciousness. Most of our cognitive abilities spring from here. The neo-cortex, the latest evolutionary structure within the cerebral cortex, governs our higher cognitive behavior and our immense learning abilities. It makes up about 80 percent of the total brain-mass and is most developed among the humans. As it evolved gradually, it became progressively more and more wrinkled, the wrinkling allowing the cortex to develop much larger surface area, and hence more neurons to accommodate within the small space available inside the skull. At birth, the cortex forms a smooth covering over the structures of the brain, but as it increases in size and complexity over a period after birth, it becomes more and more wrinkled, finally teaching a total surface area of about 2800 square centimetres in a fully grown adult. The increase in wrinkling of the cortex is known as *corticalisation* and is the real measure of human intelligence. This increase in the folds of the cortex has been a major evolutionary factor that enabled a better coordination and organization of the complex behaviours in higher primates and humans. Neocortex undoubtedly is the seat of abstraction, reasoning, analysis and symbols.[8] It is the seat of mathematics, arts and music. It is responsible for our humanness, even though the higher primates and some cetaceans like dolphins and whales also have well-developed neocortex.

A larger cortex obviously houses a larger number of neurons, but more than the number what actually matters is the number of connections between these neurons that determines the responses to a given stimulus, on in the extensive neural network within the brain. Major elements of this network are the axons, dendrites and synapses. The fundamental element is of course the brain cell or the neuron. The brain and the spinal cord together constitute our Central Nervous System where the brain interprets and stores sensory information for sending orders to different parts of the body, and the spinal cord provides the pathway to carry messages from the brain to the Peripheral Nervous System, from where the parasympathetic and sympathetic nervous systems picks up signals that regulate the bodily functions respectively under ordinary conditions and under stress, and spending and saving energy.

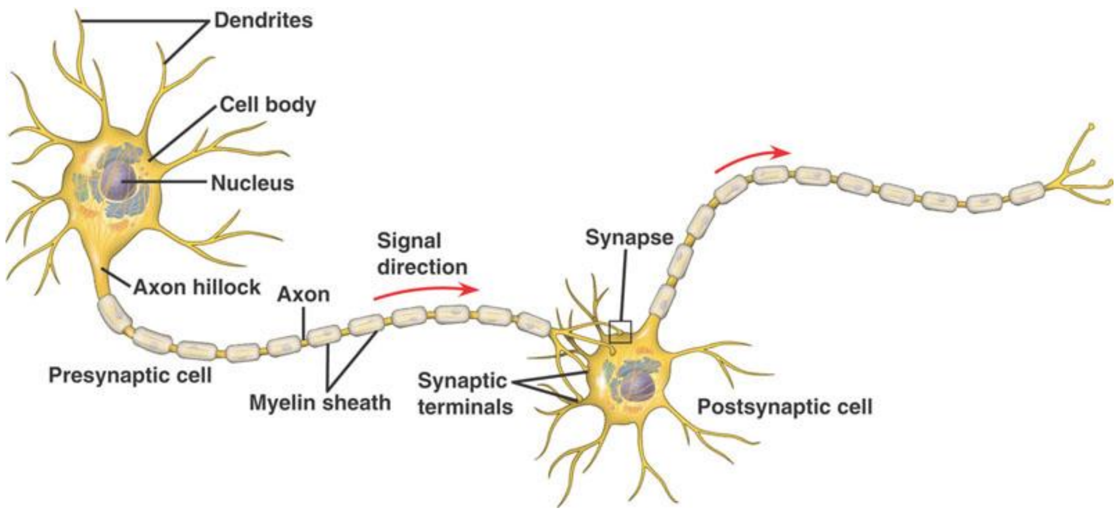
It was not until the twentieth century that the neuron was recognized as the cell of the brain. Brain tissues look like a continuous jumbled mass – a reticulum - under the microscope, without any definite cell defining membranes that distinguishes cells in every other tissue. This reticular theory of brain persisted well into the 20th century, till a Spanish neuroscientist, Santiago Ramon y Cajal, using a technique developed by the Italian anatomist Camilo Golgi of staining a few neurons so that they could be made to stand out in the jumbled morass that the brain appeared to be and studied individually, demonstrated that neurons were nothing but cells. That did not, however, convince Golgi, who remained a confirmed reticularist throughout his life. But the spectacular insight that Cajal gave into the working of the brain by suggesting that neurons were responsible for the movement and processing of information inside the brain was the beginning of modern neuroscience.

Cajal showed that although there exists a vast gulf of difference between the intelligence possessed by humans and insects or animals, such differences are not reflected in the structure of their neurons which remarkably looked similar, except for their numbers. As Cajal himself observed, "the quality of the psychic machine does not increase with the zoological hierarchy. It is as if we are attempting to equate the qualities of a great wall clock with those of a miniature watch." Human brain has about 100 billion neurons, compared to only a million neurons in the brain of honeybees, 20000 in snails and only 300 in the simplest worms. But the humans do not possess a 'super-neuron' – neurons in all living beings operate more or less in the same way by sending and receiving electrochemical impulses, they have similar complex branched structure to facilitate communication with other neurons and they are basically the same at the cellular level in every living thing. Golgi and Cajal received the Nobel Prize in Physiology and Medicine in 1906 or their work on structure on the nervous system, sharing the coveted Prize for the first time in history.

The neuron's complicated structure has evolved to enable them to perform the role of super-efficient messenger for receiving messages from and transmitting messages to other neurons. These messages are

[8] The area that is specifically involved with abstract skills like language and mathematics is called the left angular gyrus in the left cerebral hemisphere. This, together with another area called the supramarginal gyrus related to skilled action like waving our hands, distinguish us from the apes, who lack these areas and hence these abilities.

nothing but the electrical impulses generated within the cell by the action of the ions within and outside the cell membrane. The parts of the neuron that receives messages from other cells are called dendrites[9] which are like tendrils propagating from one end of the neuron; they are attached to the cell body or soma that contains the cell nucleus. Attached to the soma are the axons which like optical fibres carry the messages to other neurons and are protected by the myelin sheath composed of fatty substances. Neurons, however, constitute only one tenth of the cells in the brain, the rest being the glial cells - grey fatty cells that support the neurons – providing insulation and delivering nutrients to them, producing myelin to coat the axons, and also cleaning up the wastes and removing dead neurons.



Structure of Neuron

Each axon has several terminals to connect to the dendrites of neurons that receive messages; these terminals are fitted with tiny sac-like structures called synaptic vesicles which are filled with chemicals suspended in fluid; these chemicals are called neurotransmitters[10]. An axon can connect to thousands of other neurons via their dendrites. The junction between two neurons consists of a minute gap – called the synaptic gap - across which neural impulses pass by diffusion of a neurotransmitter; this junction is called a synapse. Synapses act like gates, and regulate the flow of information, i.e. electrical impulses that travel along the axons, within the brain, which is unidirectional. Through the synapses, neurons connect to the incredibly complex and super-organised network of neurons that can process information and pass it down to all parts of the body via the bunch of nerves running through the spinal cord and reaching all parts of the body. Different structures and parts of the brain establish connections amongst themselves forming neural circuits that pass and process information back and forth, allowing the entire brain to work in unison, producing sublime perceptions or ideas.

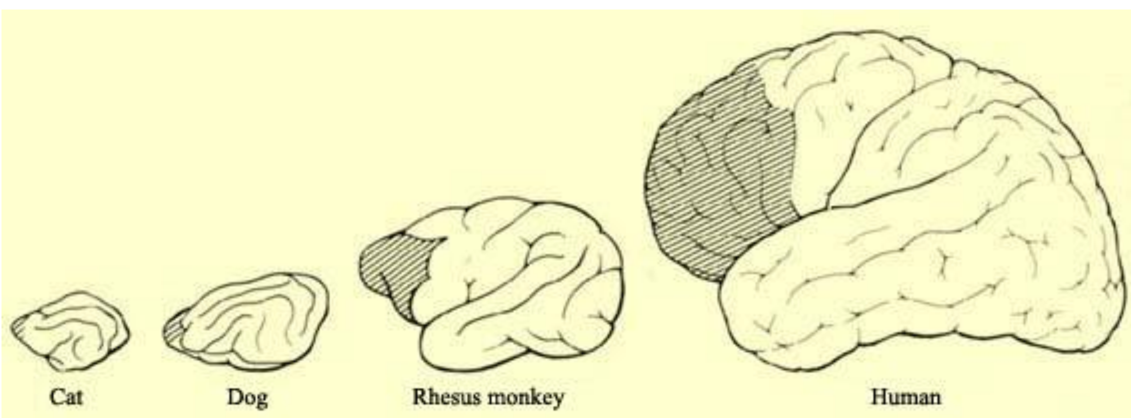
Billions of neurons inside the cerebral cortex thus create an amazingly intricate and astonishingly complex web of interconnections that account for the progressively complex of behaviour and sophisticated thinking among higher mammals and humans. Organisation of the vertebrate brain also shows striking

[9] Dendrite means ‘branch’ since it resembles the branch of a tree.

[10] Common neurotransmitters are acetylcholine, serotonin, dopamine, noradrenaline, endorphin etc.

similarity. All vertebrates have a forebrain, midbrain and hindbrain, and within these, neural systems that perform common functions, though different species have specialized areas within their brains to deal with the specific constraints and circumstances of their respective environments. In order to facilitate development of higher cognitive abilities, the structure of the human brain that has grown the most is the neocortex. Our superior ability to anticipate and plan for abstract reasoning have all resulted from a highly developed neocortex, in particular to the denser interconnections between the prefrontal cortex and the rest of the brain. The growth of neocortex was higher among the higher primates and humans; this might have been necessitated by the demands of growing complexity of their social lives which would include the ability to predict the behaviour of other individuals within the group. Natural selection would thus favour the development of areas in the cortex that are responsible for language and communication which improve the social skills.

Within the temporal lobe and prefrontal cortex of the brain lies a special class of nerve cells called ‘mirror neurons’, which fire not only when we perform some actions, but also when we watch someone else perform the same actions. These mirror neurons are believed to have played a major part in the transmission of human culture and in shaping human social behaviour. In doing so, they may have played a major part in making the *Homo sapiens* what they are today.



Relative sizes of the prefrontal cortex in animals and humans

The complexity of the human brain has been the result of hundreds of millions of years of evolution. Starting with the Reptilian brain, the limbic system or the ‘mammalian brain’ and neocortex or the ‘thinking brain’ had evolved over a period of 500 million years, but at each stage the brain had retained its older structures which were useful in fulfilling the fundamental needs of life. Thus instead of discarding these structures, evolution had adapted them, through a process of building expansions and extensions around the older structures, rather than rebuilding everything from the scratch. And sure enough, even the human foetus has retained the memory of such development. Brain of a human foetus also develops from inside out mimicking its evolutionary stages, starting with the neural chassis which is the brain stem, then the R-Complex and following it up with the limbic system and finally the neocortex. Memory of our evolution goes into the depth of time, far deeper than the last two hundred and fifty thousand years since *Homo sapiens* had dwelt upon this earth.

We often boast of other animals being inferior to human beings in evolutionary terms since our brain sizes are far greater than that of most animals, as if humans occupy some kind of a pride of place among all the animals. Nothing can be farther from the truth. Evolution has seen thousands of species of animals and birds and millions of species of insects succeed in the struggle for life, each species carving out a specific niche for itself in which it lives in perfect harmony with its surroundings to which it has successfully adapted itself despite their smaller brain sizes. Evolutionary success in fact has very little relationship with the brain size. Larger brains have not replaced smaller brains, but has only added to them, increasing the complexity of brain structure. The increased complexity was not the objective of evolution but a by-product of its endless experiments over endless millennia. It was only a coincidence that mammals were favoured with this complexity.

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