Neuron and Information: To Be or Not To Be?

Introduction:

Introducing a concept like information into the human being is difficult, even by asserting generically that it can be what we objectively perceive from the outside, or the data flowing into our storage systems - data that represents a starting point for interfacing with the world around us. If there is something we have learned about how all information physically situated outside of our intellectual apparatus can imprint the memory inside, is that the external world continuously releases information that we capture and simultaneously flow into our reminiscence. These are not necessarily just objects with a material form, that is, directly perceived by our innate sensorial system: in fact, although it is true that we visualize the color of the sky or the sound of an animal in our thoughts, we can also assign numerical values to certain elements, such as weight and measure, and even conceptualize abstract forms such as economics, politics, or even the subject of this discussion.

The word "information", in fact, etymologically means "without form". We could propose many other examples, but as suggested by those who have tackled this problem before us, it is impossible to discuss any topic without having an unequivocal common term of reference. To apply this definition to what we are talking about, we could formulate the following question: in what exactly information consist of, and how can it be defined unambiguously?

The Classical approach:

To frame what information is, we could start from the definition cited at the beginning and assert that consists of what we know, or what we have learned by memorizing a certain amount of data processed in a respective period of time, limited to our acquisitive and assimilative abilities. We assume, therefore, that the final stage of this procedure can build our own memories: a classical thought, formulated since the dawn of civilizations. In fact, since information about past people's history has reached us, humans have always had a certain curiosity about where their memories are located, coming to identify them with our conscious self. This is more than a legitimate curiosity, given that in practical terms, for many people, it represents the boundary between what we define as existence and non-existence. Referring to a little history, in the past the only feasible study for centuries was the mere discussion about them (given the limited technological progress available to calculate such data), generally contextualized in terms of philosophy, theology, esotericism, and so on (just to name a few of the many doctrines that have dealt with this problem). Obviously, this may be seen by some as a reductive and unproven approach, which nevertheless indicates the significant effort made: for each human civilization we have discovered, evidence has always been found, both in written and oral transmission, of questions concerning life, death, and the afterlife. The same caution has been paid at every level in talking about it. We can cite the religious sphere, which in the majority of its doctrines sets up a dualism between the physicality of an individual and his or her incorporeal soul, without posing the problem (sometimes asserting that discussing the topic is disrespectful or forbidden) of where its hypothetical spatiotemporal location should be. From a philosophical point of view, although in principle it is possible to discuss it without preconceived dogma, approximate solutions have nevertheless been approved: without going into details, from Parmenides to Socrates, from Plato to Aristotle, from the Cartesian "Cogito ergo sum" to the finite/infinite of Hegel (just to name a few). These solutions, in fact, although not answering the problem of defining and physically/biologically instrumentally verifying information location, have always been accepted with a kind of positivistic conviction that remarkable strides had been made, even though they were actually little or nothing to do with the bases of the informative subsistence previously posed as an incipit of the research, and with defining it in an unequivocal way.

The Mathematical approach:

The classical thought previously exposed, although intuitive for us, remains deficient in countless details, starting from how we can extrapolate a specific element contained in a set of origin, or circumscribe within the total that part that is useful to us. This is useful for multiple purposes, starting from being able to reproduce and communicate it better to a third receiver. For example, let us consider the following problem: to obtain from a satellite observation of a forest the information about only the trees with yellow leaves, compared to the total of everything the environment contains. To give an approach with more technical depth (without putting aside the countless mathematicians, engineers, physicists, and scholars who have worked on it), we could cite a fragment of the theory formulated by Shannon in the first half of the 20th century, where for the first time terms such as informative entropy, self-information, and event source began to be coined. The total information (in this case, represented by the entire forest environment) can be divided into informative subsets (animals, watercourses, fish, and so on), which in turn are broken down into communicative units, that is, parts under which the axiom that we cannot descend is placed. In the example of the forest, if during the observations a yellowish stain of only withered leaves on the ground is discovered, although always probabilistically, this could indicate the presence of trees with yellow leaves, that is, that partially or totally satisfy the question. This condition of probability is defined as informative entropy: it can be said, therefore, that the yellow patch has a much higher entropy value than the common green patches, whose probability of being observed in a tree environment is greater, almost taken for granted. Obviously, further informative elements can be introduced, such as a weather bulletin that signals a sudden snowstorm: this would substantially modify the informative entropy of the green zones, as it would become more probable to observe snowy white zones, not to mention that the bulletin itself would assume a high informative entropy. In summary, the more the informative source contains repetitions, the less entropy it will probably have. Therefore, the information ***I(x)*** is calculated from $I(x) = -\log_2 P(x)$ where ***P(x)*** is the probability that that information is verified: there is an inversely proportional relationship between the information itself and its probability (high probability leads to low information quantity, and vice versa). As previously stated, communicative units from a random emissive source cannot be represented with a number of elements lower than those required to maintain their informative entropy: this is to avoid partial or total loss of the unit and therefore of the information itself.

Without delving too deeply into the details, Shannon defined the *nat* as the basic unit of measure for entropy: this is based on natural logarithms and powers, compared to base-2 logarithms that define the bit (this deliberate association was due to the fact that one of the purposes of the information theory was to apply it to the binary systems of electronic computers), therefore a *nat* was approximately equated to 1.44 bits or $\left(\frac{1}{\ln 2}\right)$. Moreover, Shannon himself wrote: "***N*** random variables, each with entropy ***H(x)*** can be compressed into fewer than ***NH(X)*** bits with a small probability of information loss as ***N*** tends to infinity; conversely, if compressed into less than ***NH(X)*** bits, it is virtually certain that some information will be lost."

Therefore, the concept of self-information can be introduced, that is, the information obtained from the certain affirmation of the event itself; to change perspective, it can also be defined as the amount of uncertainty associated with the realization of an event, that is, an event occurs when the uncertainty that it may not occur is removed. The relationship between uncertainty and probability is closely related: without uncertainty, there is no information, and the more uncertainty there is in the random signal, the more informative it is to reveal the nature of the signal (that is, it is also informative to understand what it is and what it is not). To understand the close relationship between the concept of self-information and its probability of occurring, the following association can be made: the self-information of an event A that has a probability ***p(a)*** of occurring is the amount , that is, $I\ :\ A \to \log \frac{1}{p_A}$ that is resolved in $I\ :\ A \to -\log p_A$.

This definition satisfies all the elements of the probabilistic calculation in question. As mentioned above, the probability of the emitted information may depend on events that have occurred previously: this is called a source with informative memory, that is, with dependence on the state of the source, (source with memory). The informative entropy of sources with memory is obviously lower than that of a source that does not have it, because in this context the emitted events may depend (to a certain extent) on those emitted previously, which makes them more predictable.

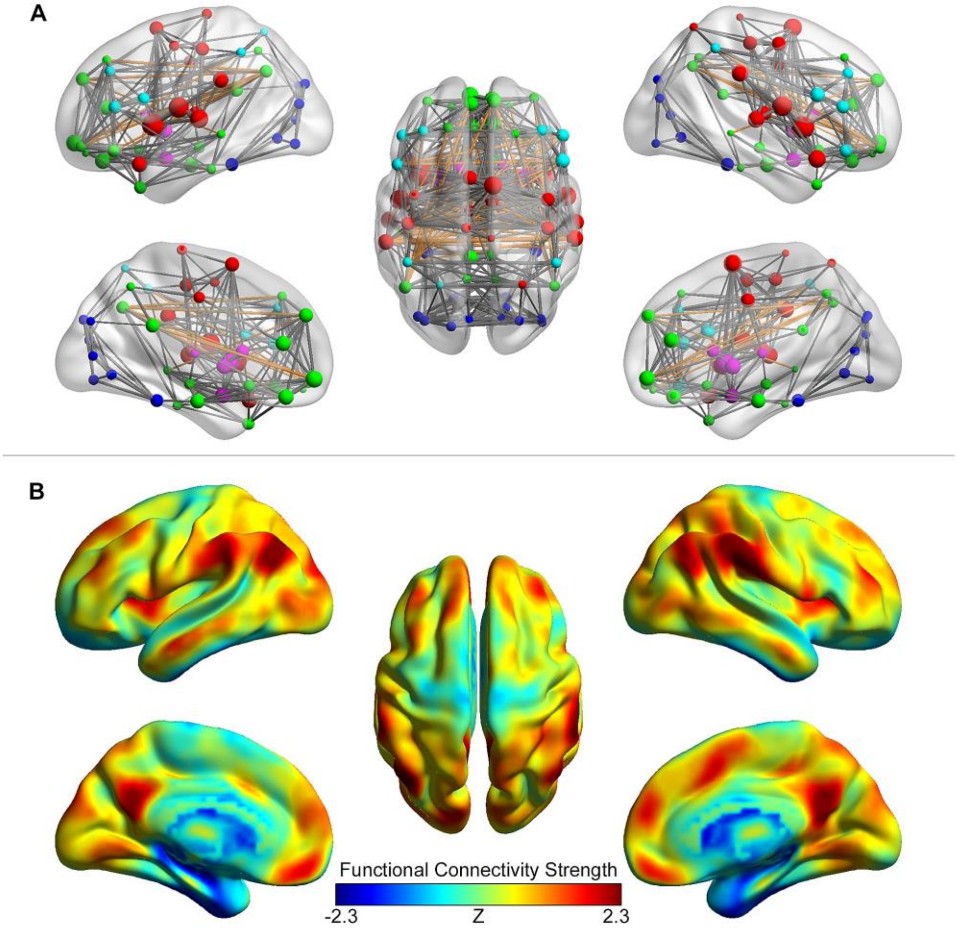
Without going into further mathematical details, it can be seen from this model that the information of an event can be seen as the quantity of certain elements that define the event itself, actually happened, with respect to all the other possible ones. Logarithmic probability because separate events are considered whose probability of occurring is the product of the individual probabilities, so that the total *informative entropy* is the sum of the informative entropies of the individual events. From this approach, it becomes possible to unequivocally define how, from any perspective we can identify it, what has been identified as a form of existence not only must necessarily possess *informative entropy*, but the way in which it can be catalogued must necessarily have been defined unambiguously; conditions that represent an inescapable and defining cornerstone for our own universe. Therefore, it becomes possible at this point to expand the spectrum of definition and manifestation of reality itself: from what we can directly perceive (heat or light limited to temperatures and frequencies detectable by our sensory and visual field), to what we cannot even perceive (infrared or ultraviolet light), from what is possible to detect with the help of our technology (life forms invisible to the naked eye present in the microcosm), to what we cannot currently detect but of which the effects have been hypothesized (phenomena that we define as dark matter and energy in the macrocosm are part of this category): all these elements in fact contain informative entropy in any form and size, and therefore information.

Information Entropy in neurons:

To understand how the application of the theory of informational entropy can facilitate the selective study and analysis of brain synaptic activity, it is useful to imagine a set of neurons as a system that resides in a base state: that is, let us assume that the majority of neurons are in a state of active synapses, compared to those that are in the resting potential state (the premise that the neural area in question is always with a greater percentage activated derives from the physiological condition in which normally active synapses are always present in a very large number, and those at rest are activated by a response to an external stimulus independent of the existing condition). Such an abstract simplification helps to capture the essence of the entropic interpretation of the brain function in the absence of activation stimuli. By associating then the neuron activation in Boolean conception (bearing in mind the similarity itself of the neural all-or-none impulse to a binary system), the resting potential state can be set to "0" and the activated state to "1". In a neural set of size N, therefore, there can be 2^n possible ways in which the activation patterns of the set itself can combine: if N=3 there will be 3 neurons (n1, n2, n3) and their activation path can be organized into 2^3, that is (n1=0, n2=0, n3=0), (n1=0, n2=0, n3=1), (n1=0, n2=1,n3=1), until arriving at (n1=1, n2=1, n3=1). If it is assumed that only a minimum number of these possibilities can represent the state of a specific brain area in resting potential, it becomes evident that the arrangements of the activated state of the area far exceed the representation of the brain function in its resting state. Continuing on this line of abstraction, therefore, many states in which active neurons can activate the neural area representative of brain function at rest are possible. Therefore, assuming that one or more stimuli occur in this system, there would be a higher probability that the reference neuron set could also activate the resting area. Referring, for example, to the equation of informative entropy contained in an informative source with a variable of the set of values with finite (or discrete, mathematically speaking) number $H = -\sum_{p_i} p_i log_2 \left(p_i\right)$, where with ***H*** we can mean the already calculated entropy, and pi is the possibility that an informative event i may occur (that is, an event possessing greater informative entropy), the correlation between a single event with high informative entropy and the entropy of the set that increases during the response to the stimulus itself is highlighted. Using the base-2 logarithm (which, as proposed by Shannon, is also easily adaptable in computer models), it is possible to identify, for example, the correlation between neural impulse, resulting neural response, and informative entropy present before and after.

Without delving into further mathematical details, starting from this first approach up to the correlation between cerebral areas through functions with continuous variables (that is, not finite), it has been possible to numerically define the difference between the stages of neural activation from the cerebral cortex "at rest state" to its state of activation in specific areas, starting from motor functions and up to receptive, sensory, and cognitive reasons, as widely demonstrated by the multiple studies carried out through the detection of the brain's electrical activity itself and functional magnetic resonance, data that have represented the basis for the modern definition of brain entropy itself.

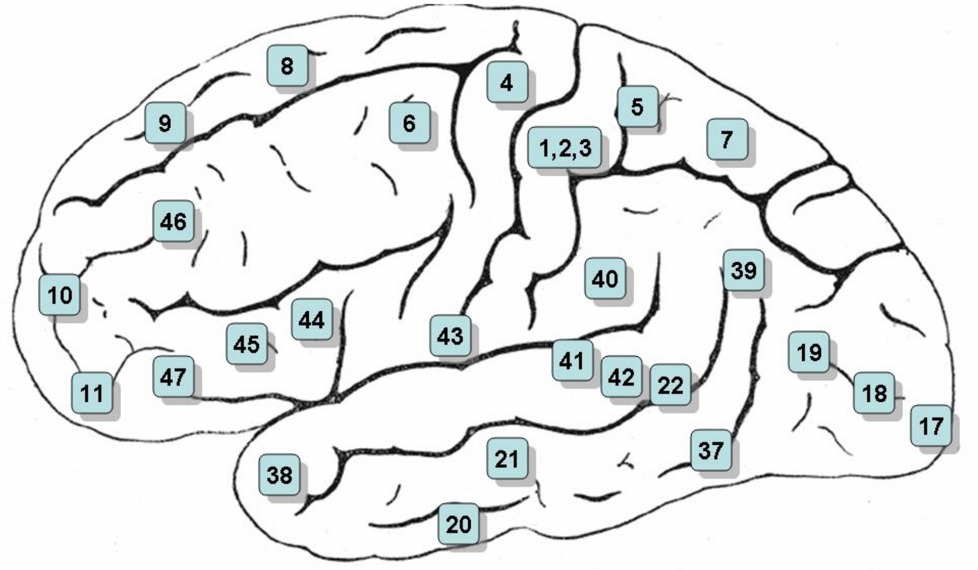
Application of “Entropy Information” calculated in specific human brain cortex areas by functional active connections spike (Software BrainNet Viewer)



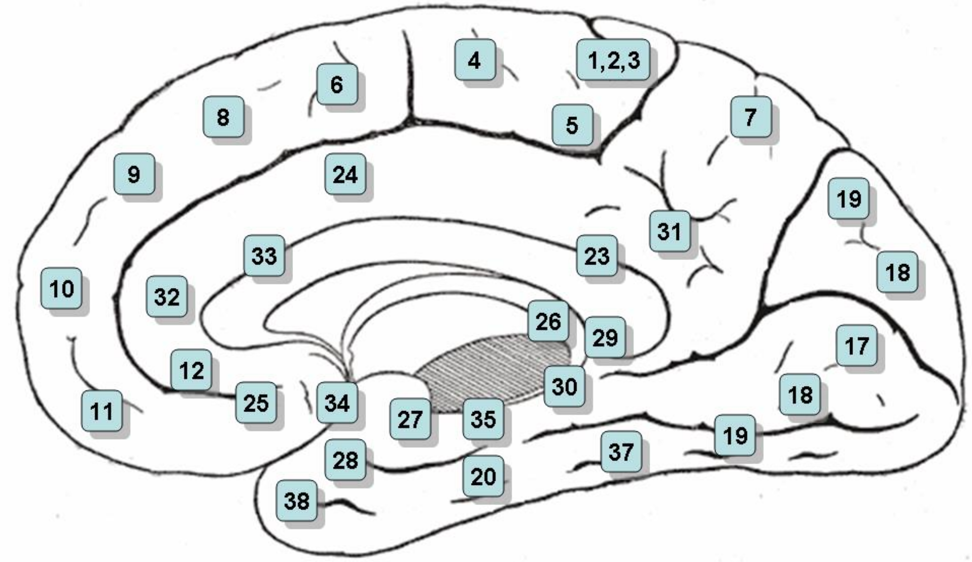
The Central Nervous System:

Thus, one can define as an exaggeration the delicacy on one hand or the technicality on the other with which the theme of our existence has always been treated, regardless of the nature of the assertions elaborated regarding it (namely, whether they may have arisen from both scarce scientific evidence and more accurate mathematical or physical bases). Modern science could respond to this question: the localization of our memories, even according to the most recent analyses, is among the most complicated things we have ever encountered (as is its very functional structure), therefore the caution of the approach in the doctrine of thought, being universally, in the literal meaning of the term (it is really appropriate to say so), a topic of difficult disquisition compared to any other term of comparison, does not seem unwarranted. Fortunately, thanks to a more rational and less dogmatic vision (which starts from representations through mathematical models like those exposed before, up to the latest technological tools at our disposal), steps have been taken forward, at least at a cellular and medical level: it is now universally accepted by the scientific community that our thoughts, our memories, and therefore our existence, are contained in what is defined as the cerebral cortex (with particular reference to the hippocampal area), also called gray matter, with a thickness ranging from 2mm to 5mm. It is a continuous layer that tends to extend on the plane, representing the outermost part, i.e. the telencephalon (i.e. stratified in the terminal zone) in all vertebrates: it is made up of neurons (i.e. cells called cerebral cells), glial cells (which have nutritional tasks for the neurons themselves and ensure the insulation of nervous tissues and protection from foreign bodies in case of lesions), and unmyelinated nerve fibers (i.e. without lipid-protein insulators). The cerebral cortex is the focal point of all our complex cognitive mental functions from thought to memory, from sensory receptors to language and so on; it is part of a larger structure: the brain, which in turn is part of the central nervous system. In nature, everything is defined by a peculiar structural scheme and the mode in which our synaptic system is formed is not an exception, neither in terms of constitutive temporal precision nor complexity. Assuming, to date, the absence of a unified agreement in the scientific community on when neural electrical activity can actually begin (this is also due to difficulties in detecting it with non-invasive methods, although examination through electroencephalography has shown data not always stable from the third week onwards), the neurogenesis process, i.e. the formation of neurons, is better understood. The latter already starts from cellular gastrulation (the phase in which cells divide to form vital organs) which occurs from the second week of gestation, after which the neural plate begins to form. Between the third and fourth weeks, neurulation is evident, a phenomenon in which the neural plate gradually expands (bending and sinking inside the embryo giving rise to the neural tube, which will form the central nervous system and the spinal column) defining the regions in which cells differentiate for tasks and functions. After the closure of the neural tube, true neurogenesis starts, starting from the cerebral stem cells themselves, which differentiate into the different known types of neurons. The central nervous system is composed of the brain (composed of the cerebrum, diencephalon, cerebellum, and brainstem with neurons generally placed in the supracortical zone) and the spinal cord (also rich in neurons but located mainly in the subcortical zone and covered by the so-called white matter, conversely to the cerebral cortex). The neural production rhythm increases from the seventh to eighth week, up to the last months of gestation, reaching a limit of about 250,000 neurons per minute; in the last month, this process slows down and neural connections begin to be created, discarding neurons that are unable to create synapses among each other. In all this period, from 80 to 100 billion neural cells have been formed, a number that is anything but negligible considering that they are contained in an average of 1200cm^3 with a weight of 1.4kg. Also under discussion is neurogenesis in individuals after birth and after maturity, i.e. the production and purpose of new brain cells throughout life: if, on one hand, some more recent ones have been observed compared to the biological age of an individual, on the other hand, it has been found that their number is limited compared to the immense production developed before birth. Even the number of synaptic connections is far from negligible: considering that each neuron of human primates makes from 1000 to 10000 junctions with neurons nearby, one can easily imagine the immense quantity of managed connections, i.e. a number ranging from 1014 to 1016 synapses. Come accennato in precedenza, la corteccia cerebrale si occupa di tutte le nostre funzioni neurali complesse: tali funzioni sono svolte in aree delineate con funzioni specifiche altresì chiamate *aree di Brodmann*. Although these represent a wide and comprehensive differentiation of the organizational system of the primate cerebral cortex, it should be added that they have been the subject of scientific debate since the sectoral localization of synaptic functions was hypothesized, as they are defined only based on the generic neural organization and not strictly correlated to specific cortical functions: in fact, to accurately determine to which area a portion of an individual's cortex belongs, histological examination is necessary. In addition, some areas have not been entirely confirmed as they were detected only by neurophysiological or magnetic resonance examinations: this further confirms how complex cerebral organization is. Below is an exemplary diagram with its corresponding areas of interest; this diagram refers to the original denomination with some areas themselves subdivided into correlated subzones for tasks.

Lateral and Median Brain Broadmann Areas:



Median Broadmann Areas:



Areas 3, 1 and 2 - Primary somatosensory cortex (listed in the sequence "areas 3, 1, 2" for convention).

Area 4 - Primary motor cortex.

Area 5 - Somatosensory associative cortex.

Area 6 - Premotor cortex and supplementary motor cortex (secondary motor cortex) (supplementary motor area).

Area 7 - Somatosensory associative cortex.

Area 8 - Includes the frontal eye fields.

Area 9 - Dorsolateral prefrontal cortex.

Area 10 - Anterior prefrontal cortex (most rostral part of the superior and middle frontal gyrus).

Area 11 - Orbitofrontal area (orbital gyrus and rectal gyrus, plus part of the rostral area of the superior frontal gyrus).

Area 12 - Orbitofrontal area (previously included in BA11, it is the area between the superior frontal gyrus and the inferior rostral sulcus).

Areas 13 and 14 - Part of the insular lobe.

Area 15 - Anterior temporal lobe.

Area 16 - Area present in cercopithecine primates (a family of monkeys found in Africa).

Area 17 - Primary visual cortex (V1).

Area 18 - Secondary visual cortex (V2, V3, and V3A).

Area 19 - Associative visual cortex (V4 and V5).

Area 20 - Inferior temporal gyrus.

Area 21 - Middle temporal gyrus.

Area 22 - Superior temporal gyrus, its caudal part is considered as the location of Wernicke's area.

Area 23 - Posterior cingulate cortex, ventral part.

Area 24 - Anterior cingulate cortex, ventral part.

Area 25 - Subgenual cortex (involved in depression, part of the ventral-central prefrontal cortex).

Area 26 - Ectosplenial area of the retrosplenial region of cerebral cortex.

Area 27 - Piriform cortex.

Area 28 - Entorhinal cortex, posterior part.

Area 29 - Retrosplenial gyrus.

Area 30 - Part of the cingulate gyrus.

Area 31 - Posterior cingulate cortex, dorsal part.

Area 32 - Anterior cingulate cortex, dorsal part.

Area 33 - Part of the anterior cingulate cortex.

Area 34 - Anterior entorhinal cortex (in the parahippocampal gyrus).

Area 35 - Perirhinal cortex (in the parahippocampal gyrus).

Area 36 - Ectorhinal area, now part of the perirhinal cortex (rhinal sulcus).

Area 37 - Fusiform gyrus.

Area 38 - Temporoparietal area (the most rostral part of the superior and middle temporal gyrus).

Area 39 - Angular gyrus, considered by some as part of Wernicke's area (word-deafness).

Area 40 - Supramarginal gyrus, considered by some as part of Wernicke's area.

Areas 41 and 42 - Auditory cortex.

Area 43 - Gustatory cortex, subcentral area (between the insula and the postcentral gyrus).

Area 44 - Operculum, part of the inferior frontal gyrus and part of Broca's area.
Area 45 - Triangular part, part of the inferior frontal gyrus and part of Broca's area.
Area 46 - Dorsolateral prefrontal cortex.
Area 47 - Orbital portion, part of the inferior frontal gyrus.
Area 48 - Retrosubicular area (small part of the medial surface of the temporal lobe).
Area 49 - Parasubiculum area in rodents.
Area 50 - Linked to the temporal gyrus, not yet clear whether it is integrative of areas 22 and 23 or has specific functions.
Area 51 - Prepiriform area present in raccoons, a mammal in the family Procyonidae.
Area 52 - Parainsular area (at the junction of the temporal lobe with the insular lobe, present in some non-human primates with the function of drawing attention).

Note: areas 16 and 52 belong to non-human primates, area 49 has been identified in some families of rodent mammals, while area 51 has been observed in some raccoons.

In addition, it should be noted that the telencephalon is not a single layer but is itself divided into two formations, called hemispheres and connected by what is defined as the corpus callosum. The main function of the corpus callosum is to allow the exchange of motor, sensory, and cognitive information between the various lobes of the two cerebral hemispheres: it is, in fact, composed of a dense bundle of axons, which behave as conductive channels of cerebral impulses. The hemispheres are practically identical and specular from a physical/volumetric point of view, but with different (or inverted as in the visual and auditory cortex) functions compared to their left or right corresponding parts.

To summarize, the functions of the left cerebral hemisphere are:

The voluntary movements of the right side of the human body.

The ability to articulate speech and produce written text. This skill resides in Broca's area, named after neurologist Paul Broca (areas 44 and 45 according to Broadmann's nomenclature).

The comprehension of language; this ability is shared between Broca's area and Wernicke's area, named after psychiatrist Carl Wernicke (area 22 according to Broadmann's nomenclature).

Logical reasoning.

The ability to perform calculations. This ability takes place in the lower parietal lobe.

Analytical thinking.

On the other hand, the functions of the right hemisphere are:

The voluntary movements of the left side of the human body.

The ability to identify objects.

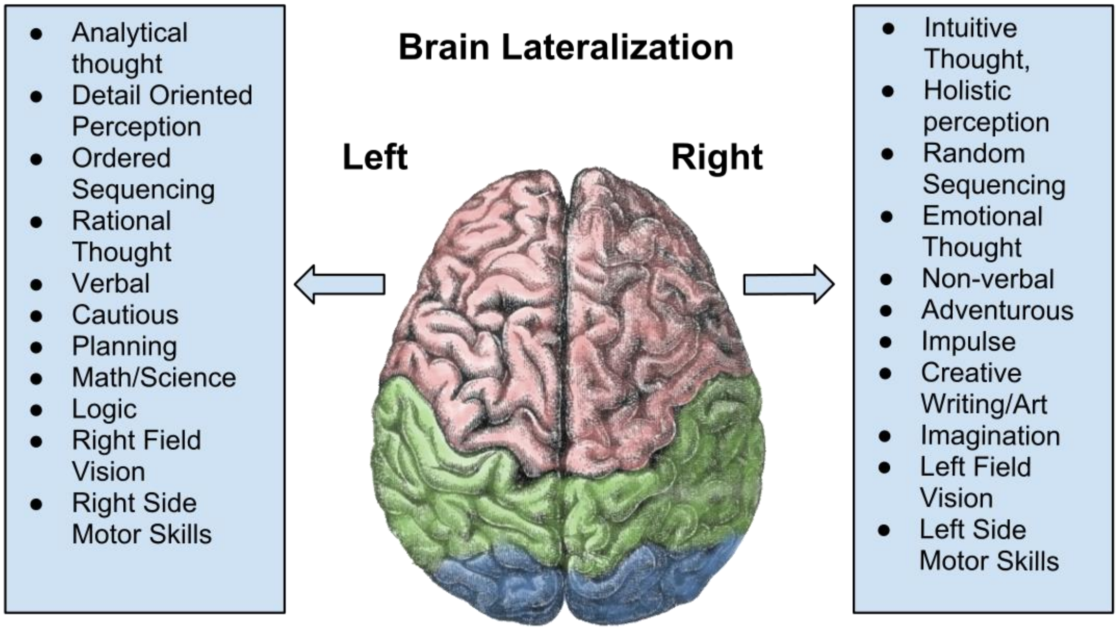
Spatial orientation.

Creativity and imagination.

Intuition.

Intonation and emphasis in language.

Graphic representation of the functions of the hemispheres



Analysis and classification of Neural Cells:

Neurons are somatic cells (meaning they make up the body of an organism), therefore their soma is similar to any other somatic cell in our body. The differences that make them suitable for synaptic functions are mainly characterized by the two cytoplasmic extensions they present: these in turn differentiate into dendrites and axons. Dendrites are used to receive signals from neighboring neurons, their number is determined by their function, and they direct the received impulses to the center of the cell, while the axon is a unique extension (as each neuron only has one) that allows it to reach other neurons. In the terminal part of the axon, there are the so-called synaptic buttons that also connect with dendrites (or directly to the soma) of other neurons. This process is structured in such a way as to be able to propagate every impulse in a cascade, triggering that chain reaction fundamental for the functioning of the neural network itself. It is important to note that the axons of neural cells can be covered by two protective membranes (the neurons of the cerebral cortex belong to this category, while for example the neurons that transmit electrical impulses to involuntary muscles are not): this covering protects the axon preventing the dispersion of electrical impulses. The outermost membrane is called the neurolemma (or Schwann sheath), the innermost is called the myelin sheath. Along the neurolemma, there are interruptions, at which the myelin sheath ends and they are defined as Ranvier nodes: these are in fact open zones that expose the axonal membrane to the extracellular environment ensuring faster conduction of nerve impulses (saltatory conduction) precisely because, being myelin an electrical insulator, the electrical potential can propagate by jumping from one node to the other thanks to the small charge dispersion.

Neurons can be classified based on the number and branching of their extensions, obtaining in this way:

Unipolar neurons: the nucleus has the value of a receptor site.

Bipolar neurons: they have a single dendrite that articulates at the antipodes of the soma.

Multipolar neurons: they show multiple dendrites.

(remember that each neuron has only one axon)

In addition, it is possible to classify neurons based on their appearance:

Pyramidal, in which the dendrites at the base are distributed horizontally, while the apical dendrite develops in height. The axon extends into the cortical zones of the cortex.

Stellate, also called granules, in which the dendrites branch out in the immediate vicinity of the soma and the axon communicates with adjacent cells.

Fusiform, having two dendritic terminations at their ends and the axon heading towards the more superficial layers.

Each neuron is involved in performing a series of functions, which is why it is also possible to distinguish them into:

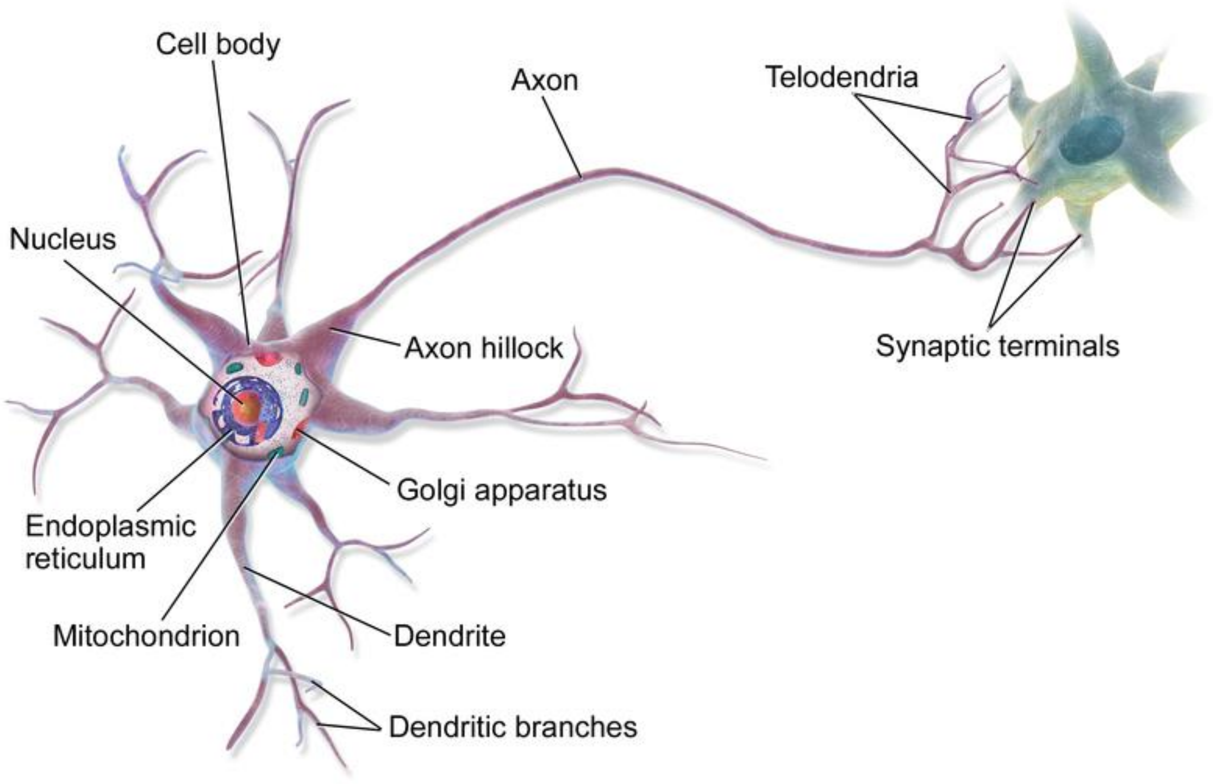
Sensory or afferent neurons: receive stimuli and transport information from sensory organs to the central nervous system.

Interneurons or relay neurons: integrate the data provided by sensory neurons and transmit them to motor neurons.

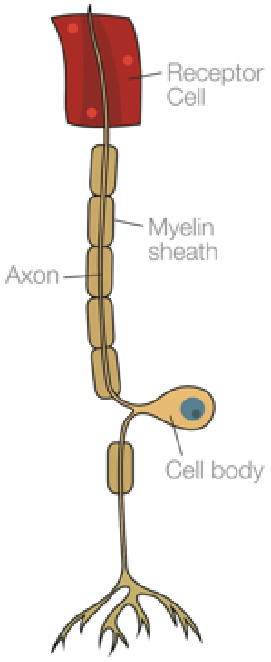
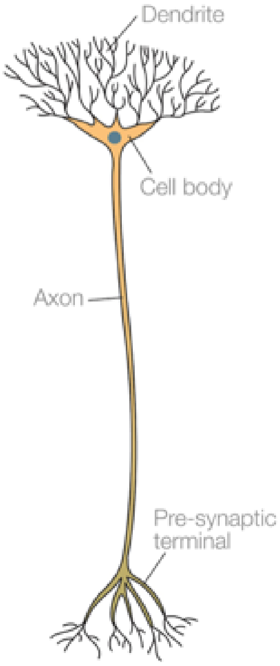
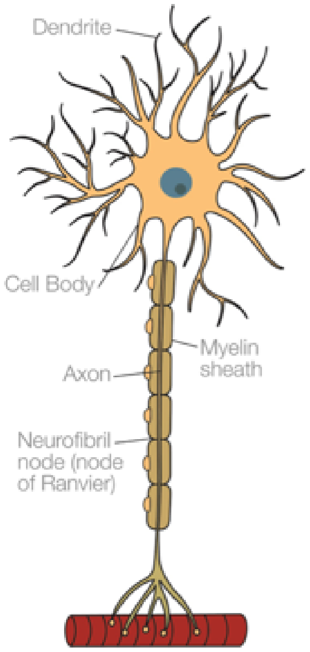
Motor neurons: transmit motor impulses to the peripheral organs of the body. They are further divided into somatomotor neurons, whose axons form fibers called efferents that innervate the voluntary striated muscles of the body. They are further differentiated into α motor neurons, responsible for actual contraction of the striated muscle fibers, and γ motor neurons, which innervate proprioceptive sensory organs called neuromuscular spindles that are intercalated in the same muscle structure.

Visceroeffector neurons: are involved in the responses of involuntary or visceral muscles. They are characterized by giving rise to fibers called preganglionic (from the spinal cord to the ganglion) that always connect to a second neuron located in a sympathetic or parasympathetic ganglion, from which postganglionic fibers (from the ganglion to the spinal cord) originate.

Graphic representation of the structure of a neuron



Examples of neuron types

SENSORY	**RELAY**	**MOTOR**
		

Neurons are also classified according to the type of neurotransmitter they use, and there are several types of neurons:

- Cholinergic neurons: they use acetylcholine as a neurotransmitter.
- Monoaminergic neurons: they use serotonin and catecholamines as neurotransmitters.
- Aminoacidergic neurons: they use gamma-aminobutyric acid (GABA) as an inhibitory neurotransmitter.
- Glutamatergic neurons: they use L-glutamate as an excitatory neurotransmitter.

The Sodium-potassium Pump in Neurons:

The functioning of cells (and therefore our entire organism) is regulated by electrical activity. This electrical activity dictates our heartbeat, the assimilation of food, our ability to move, and even our ability to sense sounds and emit words. One of the key mechanisms that allows for this is the sodium-potassium pump (also known as the Na+/K+ ATP-dependent pump or Na+/K+ ATPase), which facilitates the exchange of molecules between the inside and outside of cells, which is vital for the life of the cell. Neurons also adhere to this rule, with the fundamental difference that this mechanism is also used for a process essential to impulse transmission, namely neural excitation.

Each neuron, at rest, maintains a voltage difference resulting from an electrochemical gradient, similar to how a battery maintains voltage between its poles. This voltage difference is derived from the concentration of sodium and potassium ions inside and outside the cell membrane. This voltage, approximately -70mV, is referred to as the resting potential of a neuron. The neural cell membrane contains ion channels, which are protein-based pores that selectively allow the passage of certain ions. These channels only open and close when a certain voltage is reached. Once this voltage is reached, ions can enter and exit, causing the cell to deviate from its resting potential.

This deviation follows certain rules: if a neuron receives small amounts of incoming signals, either singly or continuously, they result in only small fluctuations in membrane voltage (graded potential) and are not strong enough to activate a neuron, which remains at rest. The neuron only activates and generates a nerve impulse when the total sum of incoming signals is large enough to surpass a threshold potential of -55mV. Once this threshold is reached, sodium channels open. Once these channels are open, sodium ions (Na+) flow out of the cell, leading to the depolarization of the neuron, or the reversal of charge on its inner surface from negative to positive. When the voltage reaches around 30mV, potassium channels open. These channels allow potassium ions (K+) to move from the inside to the outside of the cell, slowly repolarizing the cell and restoring the negative voltage difference. During this phase, the membrane cannot depolarize as the sodium pump is closed. This phase is known as the refractory phase and is functionally useful as the signal cannot travel backward and can only propagate unilaterally forward to the next segment of the membrane. The closure of potassium ion channels occurs more slowly, lowering the voltage below the resting potential of -70mV. This is known as hyperpolarization, where potassium is free to enter, only stopping after reaching its electrical equilibrium potential, thereby blocking its further release at a voltage of around -90mV, and eventually returning to the normal resting potential. The process of cellular repolarization is made possible by mitochondria, organelles capable of producing large quantities of a molecule called ATP (adenosine triphosphate), which transports and provides the energy necessary for cell functions, allowing more sodium ions to exit the cell and fewer potassium ions to enter. It is interesting to note that during the hyperpolarization phase, the sodium pump reopens, so an electrical impulse can depolarize a hyperpolarized membrane, provided that the electrical impulse is stronger than the one required to depolarize it previously (at -90mV), while a standard impulse is only needed once the voltage returns to -70mV. The entire process of neural activation is executed in all its phases each time, without partial activation. From this perspective, nerve impulses can be associated with digital signals, as they occur at the same magnitude, regardless of the strength of the stimulus. This phenomenon is also known as all-or-none action potential. It is always necessary for the threshold voltage to be exceeded to generate the initial stimulus, and the signal will always have one direction, from the presynaptic membrane to the postsynaptic membrane. Once a segment of the membrane depolarizes, it transmits the signal forward to the next segment.

Synapses:

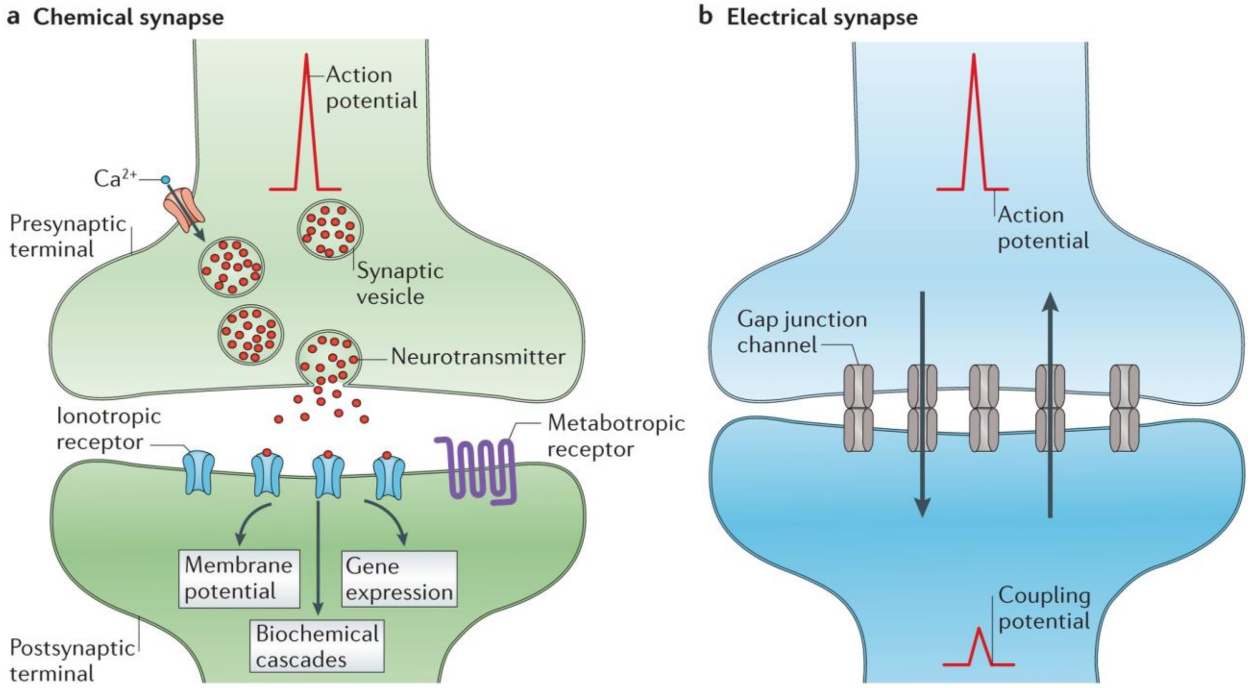
Neurons communicate with each other through intercellular connections called synapses. Synaptic communication occurs through chemical substances called neurotransmitters, which stimulate the next cell through the transmission of the nerve impulse. The nerve impulse, or action potential, propagates along the neural fiber through the aforementioned electrochemical mechanisms. The sodium-potassium pump allows the transmission of information from the axon terminal of a transmitting neuron to a receiving neuron. The sequential increase in conductance between these ions generates the action potential, causing a brief increase in electrical energy, during which the information passes from one cell to another. When the action potential is reached, vesicles on the cell surface release a neurotransmitter that quickly diffuses through the postsynaptic fiber and binds to specific molecules on the receiving cell. Additionally, the reaction with the neurotransmitter alters the permeability of the postsynaptic fiber membrane, allowing the propagation of the nerve impulse from neuron to neuron.

In areas dedicated to receiving signals from our sensory organs, these nerve impulses are produced in response to stimuli from one of our five senses (sight, hearing, touch, taste, smell). For example, in the eye, a nerve impulse is generated in response to light reaching the cells of the retina, which is then transmitted through the optic nerve to the region of the brain that processes visual information. This process is facilitated by sensory neurons equipped with specific receptors. These receptors are organelles consisting of nerve cell endings with different anatomical structures depending on the specific role each type of receptor plays. Additionally, there are other receptors found in nature, such as electroreceptors (sensitive to electrical impulses, used by fish to determine the position of their prey or others in water) or baroreceptors (found in the heart and blood vessels and serving to maintain constant blood pressure). In the central nervous system, there are both purely electrical (electro-dependent) and chemical (chemo-dependent) synapses.

Electro-dependent Synapses:

Purely electrical synapses are present in much smaller numbers than chemical synapses, although recent studies have identified more than previously thought. They are localized: - In the cerebellum (located in the back of the brain and controlling voluntary movements) - In the spinal cord (connecting the upper part of the nervous system with the rest of the body) - In the thalamus (performing an associational function between different cortical areas and regulating sensory inputs) - In the hippocampus (with functions related to memory processing and consolidation which are not fully understood) - In the olfactory bulb (an area branching from the telencephalon and receiving information from olfactory receptors) - In the retina (the inner layer of the eyeball responsible for processing visual information) Their operation is based on a cascade effect, meaning that when the voltage of one neuron changes, a reaction in a neuron connected to it is inevitably provoked. This mechanism does not allow for the integration of multiple synaptic signals, but does permit rapid communications between adjacent cells, facilitating electrical synchronization. Their presence is justified by the need for faster transmission of signals, also favoring better electrical synchronization of several excitable cells. A clear example is given by the cardiac muscle, where fibro-cells are connected through intercalated disks (i.e., contact and adherence zones between muscle fiber ends) by electrical synapses, ensuring perfect precision in muscle movements. In a system of cells connected by this electrical modality, stimuli such as a drop in pH or an increase in intracellular Ca2+ concentration induce the channel's closure and signal passage. Electrical currents propagate from one cell to another through connexons, which are protein structures with ion channel functions that contribute to forming communicating junctions existing between cells.

Differences between Electrical (a) and Chemical (b) Synapses



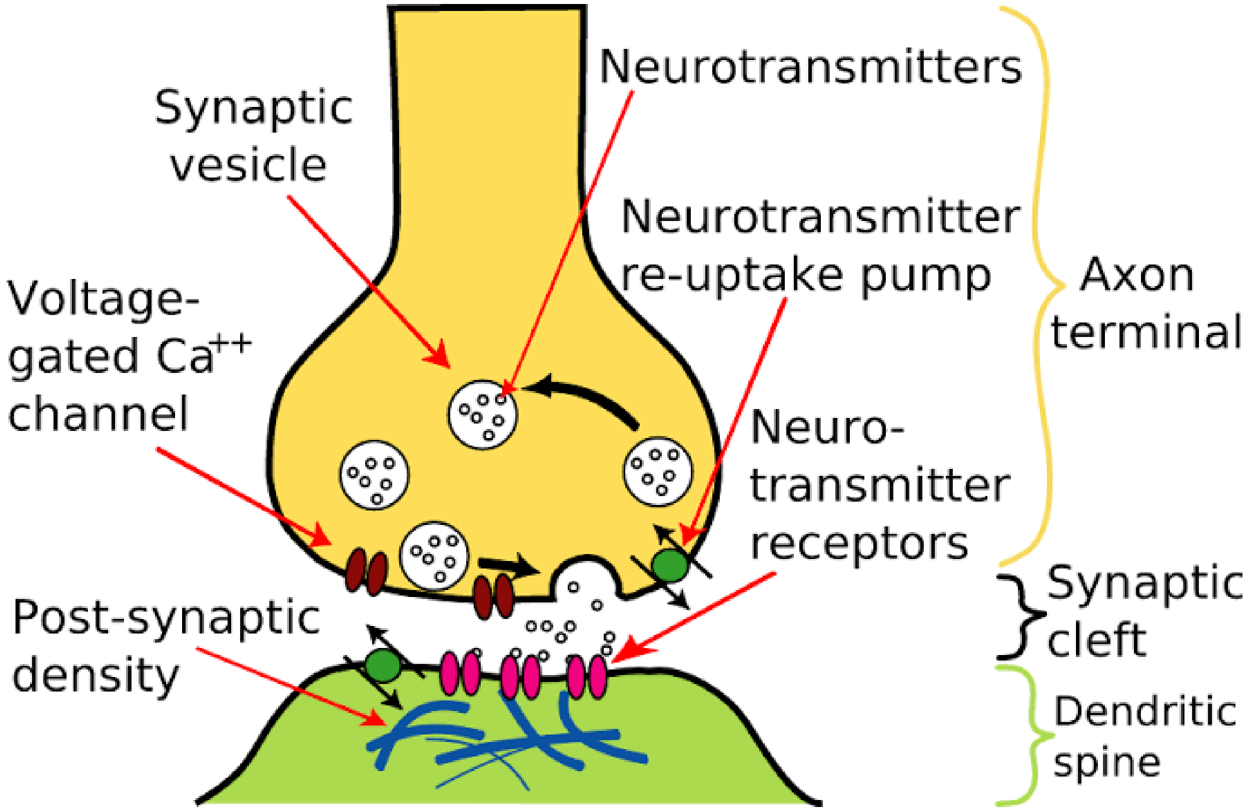
Nature Reviews | Neuroscience

Chemio-dependent Synapses:

When it comes to synapses not directly connected to precision muscles or where motor activity is not necessarily required, such as the majority of neural cells in our cortex, our body prefers the use of the chemio-dependent system. As previously mentioned, each neuron has a cell body with different branches. The smaller branches (dendrites or sensory receptors) receive signals that combine, and their total sum is transmitted through the axon branch, which carries nerve impulses from one cell body to the next.

In addition to the ionic process described earlier, the external or extracellular surface of a neuron is moistened with a salt solution containing positively charged Na+ and negatively charged Cl- ions. The internal surface has positively charged K+ ions and negatively charged proteins. The proteins inside the cell are not balanced with an equal number of positive ions, making the inner surface of the neuron slightly more negative than the external surface, forming an electrical gradient, i.e., the opposite in terms of charge of the electric field. The term chemio-dependent refers precisely to the fact that in its total operation, the membrane acts both by electrical and chemical potential. This is why we refer to it as the electrochemical potential. The higher concentration of potassium ions inside the cell causes the ions to flow outwards.

Example of Chemio-dependent impulse tranfer Synapse from Axon to Dendrite



Towards the localization of memories: scientific advancements

Given the types, mechanisms, and branching of incoming signals from dendrites and outgoing signals from synaptic buttons, how do these become "our" consciousness? This is the focal point of discussion: where are the information collected from our sensory channels and reaching the cerebral cortex stored? How can one hypothesize which relationship is created between connections, impulses, their propagation through neural areas, and our memories? How are these memories recalled as needed in our thought process?

Although there is no scientifically proven answer to every detail to date, it can be asserted that through all the studies, models, and experiments performed in every scientific field involved (some of which have been briefly described previously), a map of how synaptic areas are involved in neural stimuli has been created, and how their reactions from related events can interact with each other to generate our memories.

An important role is played by the hippocampus: this is one of the few brain areas involved in the neurogenesis process, i.e., the generation of new neurons (this peculiarity is limited to the so-called dentate gyrus, i.e., the middle part). Interest in this brain area arose after the case of Henry Molaison, an American citizen who in 1953 underwent surgery at the age of 27 (to treat a non-responsive epilepsy condition to any medication he was given up to that time) in which he underwent the removal of two-thirds of the hippocampus, the para-hippocampal cortex, the entorhinal area, the piriform cortex, and the amygdala cortex. As a result of this surgery, although he was able to recall memories of his childhood and adolescence, he no longer remembered what had happened in the 2 or 3 years prior, and some memories up to 11 years before the operation. In addition, although he was able to memorize new information, this was lost in the long term, limited to only a few days or weeks. Although previous studies had already demonstrated how important the hippocampus was in the formative and consolidative process of memories, further in-depth investigations carried out in the years that followed (until his death in 2008) showed that the damage was much more extensive than just the specific area affected by surgical removal. Therefore, the hippocampal area is undoubtedly involved in the formation of memories, but it cannot solely be blamed for the amnesias and the lack of consolidation from short-term memory to long-term memory.

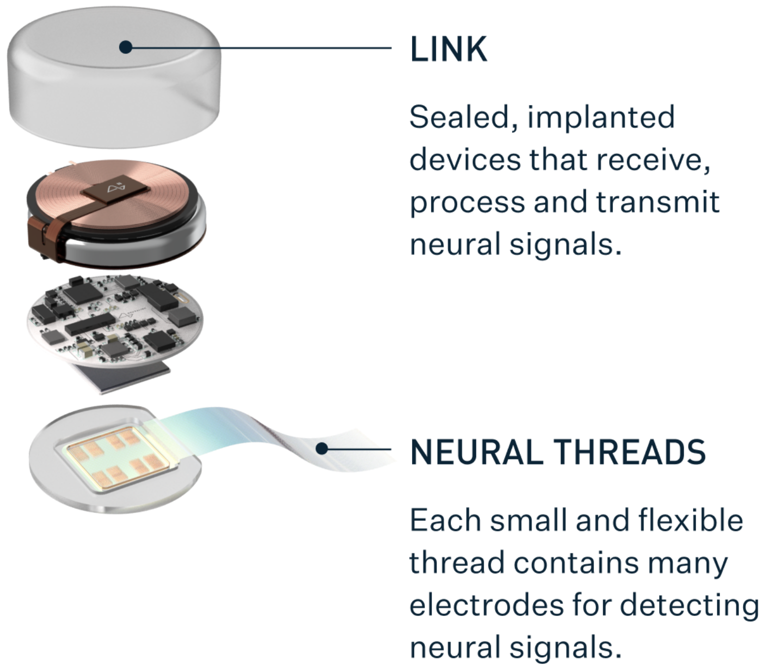
What was missing from previous technologies was the direct interfacing between neurons themselves and a system capable of receiving what actually happens within them, i.e., a way to acquire, input, and decode all the information that a synapse generates. Such technology is now possible thanks to pioneering results achieved in the field of neuroscience, through which we are not only able to better identify such areas but also the modalities and related structures involved in the process of our memories.

Future prospects towards this end include the Neuralink project, i.e., the direct connection between a specific brain area and an computer-based system. This project has demonstrated, in addition to the possibility of physically integrating neural implants in the cerebral cortex, the truth of many hypotheses raised by data gathered through synaptic processing. Among other things, Neuralink has shown that:

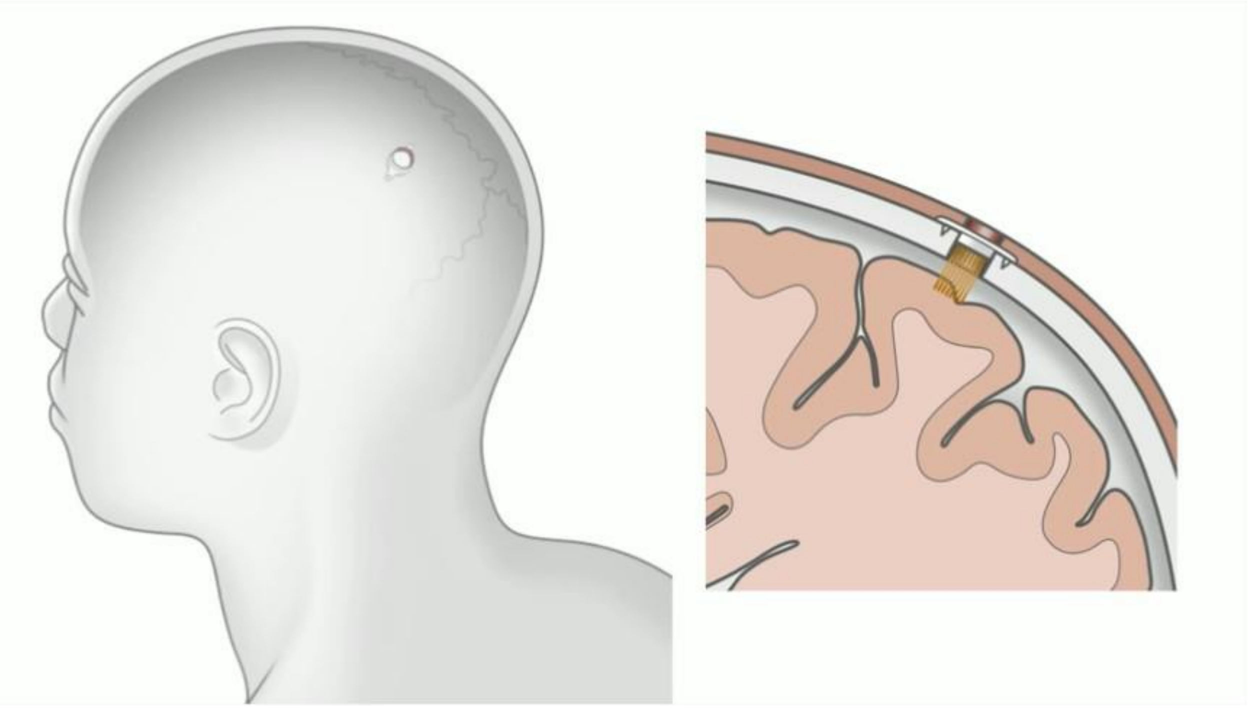
- Brain areas do not have neurons that are selectively static, i.e., neurons within the same area are continuously in synaptic communication, without a dominant neuron in terms of information compared to another (or, in information-processing terms, there is no one-way control of one neuron over another). From this point of view, the microprocessor itself is bi-directional, i.e., it can be used not only to receive signals but also to input others from the outside, integrating itself into the neural network itself.
- Precisely because of the first point, it was not necessary to connect every single neuron, as the neural network is a network of continuous impulses, and therefore, it was sufficient to connect only a limited number. Currently, a Neuralink can connect to about 1000 neurons, a number that may seem few, but considering that those neurons are also connected to all the synapses in the affected area, it has been possible to receive or transmit impulses to the entire area.

- It has also been shown that from a perspective of a brain area connected to voluntary muscles, thinking about executing a motor action or actually executing the action is identical, generating and propagating the same synaptic impulse. This has been demonstrated by interfacing the motor area of some primates (currently non-human) and connecting it to a system controlled by a mechanical control. The movement of the system was performed both with manual control connected to the limbs, and with the simulation of the same control (i.e., with the bodily movements made physically but only with the controller connected through the cerebral cortex), or without physically moving the muscles involved in the motion, i.e., with thought alone. In all experiments, the actual movement of the apparatus in question was achieved, whether it was controlled by a lever connected to the system, by a lever disconnected from the system but connected to the neural impulse, or by the neural impulse alone.
- It is still being experimented with direct synaptic connection as a redirection system for neural areas deficient in generating or transmitting ionic impulses (such as areas where there is a disruption in neuronal propagation) or where neurons have some form of structural damage (such as damage resulting from physical trauma or degradation of the axon's myelin sheath). This could bring significant medical benefits to diseases like Alzheimer's or Parkinson's, with the objective of partial or total healing from such pathologies, or even solving problems of motor paralysis due to spinal dislocation.
- It is estimated that Neuralink can also recover memories or thoughts while simultaneously introducing new ones from outside, i.e., without involvement of a learning generated by our receptive senses, a phase yet to be experimented with.

Neuralink at actual development



Schematic example of an implanted Neuralink



Conclusions:

Due to latest research, it is now possible to hypothesize in a more scientific manner where our memories are localized. Based on the latest studies and experiments, it has been analyzed that: - Within hippocampal neurons, responses to external sensory stimuli occur that push two specific genes (Fos and Scg2) in the encoding of neuro-peptide proteins (responsible for regulating neural activity itself). These are released by vesicles from the nucleus after cell depolarization, and their purpose is to establish a coordinated network with the activity of other internal neurons present in the hippocampal area, accurately favoring new signals and inhibiting others that are not related, i.e., propagating only those that are involved, pushing the network in the diffusion of new information. This could define the process of forming a memory.

So we can hypothesize that memory itself is physically the synapses impulses spread through ionic channel, both as a means of communication and as an informative purpose itself, being yet proven that neural transmission is a non-stop “all in one” cascade in the whole selective area region. In other words, we can abstractly imagine, like a closed integral, that what we are searching for is the same synaptic flow transmitted neuron by neuron in a continue loop, and not statically resident in one or more neurons.

This could bring answers to many questions:

- Over the course of our lives, a considerable number of neurons die by apoptosis (i.e., programmed cell death). This process begins from the formation of the synaptic network itself when neuroblasts are discarded, unable to form synaptic connections with others, and then increases from 30 years onwards, up to 100,000 per day in senescence. However, this does not necessarily lead to the loss of our memories: even if it has been shown that the original synaptic connections are lost and gradually renewed from 30 years onwards, our personality is still present (some believe that this leads to so-called "maturity"). Similarly, an individual can be lucid and retain memories from their youth even in advanced age, assuming no neurodegenerative diseases are occurring.

- The motivation for which a flat electroencephalogram is equivalent to the death of an individual's consciousness can support the hypothesis of consciousness as the flow of synaptic impulses. Even when neurons (after initial trauma) have not lost their ability to produce stimuli (i.e., are not clinically dead), they appear in coma situations as "empty" and unable to form connections, corresponding to non-existent neural activity (or at least not detected by current machines). One could, therefore, suppose the existence of a specific impulse or sequence of impulses that could create a chain reaction capable of reactivating brain synapses from one zone to another until potentially extending throughout the cerebral cortex, provided that neurons are intact in their electrochemical functions, i.e., the conditions for the person to emerge from an irreversible coma. This initial synaptic series of events could already be used by our nervous system in the concluding part of our gestation, i.e., from the moment when the formation of neurons finishes until the brain network is activated. Studies on the electrical activity of the last weeks of gestation are still ongoing.

Informatively Yours... Mike Yoshi.

Bibliography

- Robert M. Fano, “Transmission of information; a statistical theory of communications”.
- Soheil Keshmiri, "Entropy and the Brain: An Overview".
- Korbinian Brodmann, Laurence J. Garey, "Brodmann’s localisation in the Cerebral Cortex"
- Mingrui Xia, Jinhui Wang, Yong He, “BrainNet Viewer: A Network Visualization Tool for Human Brain Connectomics”.
- Vanputte, Regan, Russo “Anatomia umana“.
- Dr. Emilio Alessio Loiacono, "Sinapsi chimica ed elettrica".
- Journal of Neurology, “Loss of recent memory after bilateral hipocampal lesions”.
- Neuralink.com, “Breakthrough Technology for the Brain “.