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Essay

On the Mechanisms of the Human Mind

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Abstract

This paper aims to integrate some fundamental philosophical and neurobiological considerations to offer a plausible model of how the human mind works. The principal tenets of this synthetic framework are the necessity of properly distinguishing the different levels of complexity in the human brain, the importance of instruction and selection as complementary processes and the possibility of addressing the problem of consciousness with the aid of these basic conceptual and empirical tools.

Keywords: *Mind; Consciousness; Instruction; Selection; Plasticity*

Levels of complexity within the human brain

What is consciousness and how does it work? This fundamental question lies at the heart of one of the deepest philosophical and scientific problems of our time.

A purely philosophical understanding of consciousness has produced interesting and notable fruits. Some of the most eminent thinkers have examined a mystery that is intimately connected with our conception of the human being and its possibilities. However, it is important to remark the implausibility of answering the question about the nature of mind and its relation to the brain on purely philosophical grounds. The most promising tool is a neurobiological theory of mind, because after centuries of endless speculation, in which some of the brightest speculative intellects have addressed the problem, philosophy has made little progress. Philosophy can offer a solid epistemological framework, but the essence of the problem is neurobiological in nature, and as such it must be examined.

The possibility of reducing the human mind to the concomitant processes of the brain resides in a fact that cannot cease to amaze us, given the evocations of simplicity, elegance and harmony that it entails: any neural language, whether sensory or motor, perceptive or executive, is always translated into an electromagnetic signal. This code is the universal language of the brain, a highly organized system of about 85 billion neurons, a thousand times more synaptic connections on average and 50 billion glial cells disposed in a complex net of specialized cortical areas. In consequence, the integration of different sensory data is guaranteed by the existence of a universal language, of a general alphabet for all mental functions: sensitive, perceptive and those associated with the very exercise of human actions.

The aspiration to connect the molecular level with the higher cognitive functions and the work of the brain as a whole is by no means utopian. On the contrary, it stems from the evidence that it is possible to gradually unroll the Ariadna's thread that leads from the most elementary neurobiological structures to the most complex faculties of the mind.

It is true that biology and neuroscience are less susceptible than physics to the identification of common laws and general patterns of behavior. The singularity of a significant number of biological structures and the need to offer analyses operating at different levels of study make biological research strongly dependent upon new experiments and the availability of new techniques, like neuroimaging (MRI, PET..., which provides valuable structural and functional information *in vivo* of the nervous system), two-photon microscopy (capable of imaging the behavior of individual nerve cells and its constituents), optogenetics (a revolutionary method that offers the possibility of turning on or off with light genetically specified populations of neurons...) [1]. In physics, however, the possibility of advancing on purely theoretical grounds –that nonetheless need to be equally subjected to empirical contrast- is certainly higher. Thus, in biology the power of predictive reasoning, which has yielded so many fertile results in the field of theoretical physics, must be generally replaced by the careful collection of data about the specific biological systems. Induction overtakes deduction, and the importance of the details inherent to each structure, together with the specificities of biological systems, acquire unprecedented relevance when we examine the mammalian brain. For practical purposes, but on legitimate theoretical arguments, any two free electrons can be considered identical in structure and properties (their energy levels and their disposition in atomic orbitals will underlie the physical processes in which they participate). Nevertheless, the individuality of a single neuron cannot be underestimated, because the particular features of its connectivity bestow upon it an almost unique identity, which has to be adequately incorporated into any tentative explanation of cerebral activity. If in the study of many relevant physical systems I can neglect some of the interactions between its components to focus my analysis on some other factors (for example, in the model of an ideal gas, where the interactions between the particles of the gas are to a first approximation negligible), biological entities are constantly creating themselves through an exchange between the external and internal environments.

These difficulties may explain the failures of many purely theoretical models of brain action. However, our increasing understanding of the molecular foundations of cerebral architecture and mental function raises the hope of overcoming the barriers that separate the different levels of organization, from molecules to mental function.

The legitimacy of distinguishing between different levels of cerebral organization relies upon the possibility of identifying significant structural and functional innovations from one level to another (the “originality” of each level). After the work of Ramón y Cajal we know, for example, that neurons –or nervous cells- constitute the basic structural and functional units of the nervous system. Instead of creating a continuous reticule of nervous tissue, neurons enjoy individuality and establish relations of contiguity. It is therefore imperative to grant neurons, the individual nervous cells, a level of their own. Of course, the overall architecture of the brain permits us to postulate a global “continuity” among the different levels -contemplated as “potential global connectivity”-, but if we focus our study and try to delve into the different systems, it is clear that we will face almost insurmountable analytic difficulties as soon as we refrain from individualizing certain biological assemblies that share a set of commonalities, in terms of structural and functional characteristics.

From this perspective, a reliable model would at least differentiate the following levels of structural and functional organization in the brain: the molecular level, the cellular level -including the role of genes and transcription factors-, the pre-synaptic and post-synaptic levels, the level of simple neuronal assemblies, the level of complex, cooperative neuronal networks, the level of cerebral areas and finally the level of the brain as a whole in its systematic integration of lower levels and its conscious processing, in connection with the work of the entire nervous system.

All of these realms remain in constant regulation and evolution, especially through the interaction with environments of growing complexity that can exert a profound influence over synaptogenetic processes, long-range neuronal connectivity and epigenetic development. The elucidation of the degree of interdependence that binds all these factors would have not been possible without a better understanding of the flow of biological information between the genome and the proteome (mediated by the transcriptome), an achievement that represents one of the foremost advances in our biological knowledge. The traditional linear sequence of gene expression, according to which genetic information is transcribed by messenger-RNA (that is to say, fragments of DNA are copied into RNA by the enzyme RNA polymerase) and later translated into proteins, has revealed an additional step, where the proteome sends information to the genome. This mechanism, which constitutes the basis of epigenetics, adds relevant variability to the process and can elicit stable heritable traits that were not present in the initial genomic information, thereby offering essential insights on the nature of evolution.

Beyond a gene-centered view of the evolutionary process, the synthesis of genetics and developmental biology has shown a more sophisticated picture of the interaction between genetic and environmental information, where a feedback mechanism can exist between biological inheritance and the new information provided by the external world. A fundamental conclusion of the study of epigenetics points to the possibility of regulating gene expression through the assimilation of environmental information, generally mediated by mechanisms of methylation that can, for example, silence certain genes in specific biological contexts [2]. Hence, the flow of information is not simply from the genome to the proteome but also backwards, in a course that can produce significant phenotypic and genotypic innovations. Also, it is important to notice that an increasing understanding of the behavior of proteins has shown that the early view of these molecules as essentially rigid structures was incomplete. It has been replaced by a more flexible and complex model, in which the internal motions and the conformational changes thereby induced play a significant role in shaping their functionality [3].

The postulated reciprocity between the different levels implies that, in addition to bottom-up processes in which the lower levels condition the upper levels, by establishing a series of physical, chemical and genetic constraints, it is necessary to take into consideration the role played by the feedback mechanisms that operate in a top-down direction. They introduce feedback loops and therefore non-linearity into the system, such that strictly sequential processes can coexist intertwined with other operations held in parallel. Broadly speaking, these top-down interactions stay at the root of much of the neuronal plasticity that a highly evolved brain can exhibit in both its structure and its functional properties. Thus, the intrinsic variability of an environment in unceasing change is susceptible to being assimilated by a brain that, aside from genetically determined processes (in which gene networks code for neuronal networks, instead of the more simple gene-protein-phenotype traditional schematization) [4], shows an astonishing degree of elasticity in the range of its operations [5].

Instruction and selection

This combination of instruction and selection grants the brain an exuberance of configurative possibilities and can be regarded as the foundation of our behavioral versatility. The efficiency of this strategy could only be matched by a purely computational model if the instructions were able to emulate the flexibility exhibited by this mixture of internal programming and external selection. That feat will be feasible as soon as we develop sufficiently powerful computational languages with the ability of manifesting some sort of "universal intelligence," in which "learning to learn" becomes a real possibility [6], as it is the freedom from structures that show high specificity to concrete domains. However, in the evolutionary terms that define natural history it is extremely unlikely that such an "un-programmed program" (or, *stricto sensu*, a "self-programming program") could have arisen spontaneously, given the sophistication that it requires. A similar design can be more easily obtained if the mechanisms of neural growth are complemented by environmentally derived neural activity [7], thereby permitting flexible learning and increasing adaptability to a medium from which constant challenges are emanating.

Lack of pre-specification offers a vigorous way of adapting the brain to the environment and assimilating the environment in accordance with the needs of the brain. The presence of a highly flexible representational architecture and a set of powerful algorithms specialized in statistical learning [8] constitutes an example of how evolution can actually maximize its utility if, instead of creating rigid patterns between a certain neurobiological structure and its functionality, a more degenerate system is achieved. In it, the function is not necessarily specified by the structure in a bijective manner but emerges as the result of a *posteriori* specifications elicited by the challenges –both internal and external- that it has to face. Thus, synaptic specificity is not the fruit of a one-to-one biochemical matching; on the contrary, the final wiring pattern can be contemplated as the refinement of the genetically determined neuronal connections through their interaction with the environment [9]. Such a flexible system is actually similar to a fine-tuning of instructions as to enable them to cope with selective pressures, and it is probably the best way of gradually reconciling instructions and selection. From this perspective, a beautiful integration of inheritance and development stands as the primary root of the most eminent capacities associated with a highly evolved brain.

In a simplified language, if the bottom-up causal line establishes a set of constraints which limit the overall variability of the system, the top-down path amplifies the variability of the system within those constraints. Hence, the top-down interaction can be assimilated to a kind of potentiality of the system as a whole, in the sense that it benefits from the variability of the environment, thereby multiplying the possibilities offered by the innate structure and functionality of the brain (in particular, by its genetic dispositions). Both causal routes offer a pole of variability and selection, according to their internal structure and functionality, and the bidirectionality in the causal itineraries to which we have just referred does not violate the irreversibility of causality. It is certainly possible to create parallel causal lines, but at the level of each causal path, a strictly irreversible process occurs, in which sequential paths of causality lead either from a lower to a higher level or from a higher to a lower level. Likewise, it is theoretically reasonable to admit, in addition to transversal causality (between levels, in both directions), intra-causal relations taking place within each of the levels. This horizontal causality would cover, for example, internal structural and functional processes inside neurons. Of course, intra-causality paves the way for inter-causality between levels, and the latter redefines the internal interactions at each level.

The integration of data and models will permit us to grasp the chemical mechanisms that underlie the less "tangible" operations of the brain -especially in the realm of its higher cognitive functions-, in order to bridge the different levels. For example, recent progress has expanded our understanding of how memory storage works at a molecular scale. From the basic levels, like the functional organization of neuronal circuits in the cerebral cortex (including the prominent role played by structures like the hippocampus in storing memory) [10], to the study of the most complex tasks that the human mind is capable of executing (like the higher brain mechanisms underpinning literacy, numeracy and social cognition) [11], a bottom-up approach can exhibit its full potential for fruitfully harmonizing a reductionist approach and an integrative, holistic perspective, whose division obeys practical motives instead of emanating from an intrinsic impossibility.

The study of a form of synaptic plasticity known as "long-term potentiation" has highlighted the importance of this mechanism -and of neuronal plasticity in general- for spatial memory and learning [12]. Eventually, this progress may lead to a mechanistic, neurobiological foundation of some of the most important psychological discoveries regarding the types of memory and their differentiating properties [13]. Also, the basic molecular mechanisms and actors (second messengers like cyclic adenosine monophosphate, enzymes like protein kinase A, transcription factors like CREB…) are conspicuously similar to those involved in the processing of some elementary forms of non-declarative memory in invertebrates, manifesting analogous metabolic routes [14].

Research on the elementary forms of learning in *Aplysia californica* has revealed the existence of two classes of neural circuits involved in the storage of short-term memories (or ephemeral manifestations of learning). The mediating circuits are capable of inducing specific behaviors in a direct way, and they are genetically determined. The modulating circuits regulate the intensity of the synaptic connections, while interneurons play a fundamental role in their action, because they control, heterosynaptically (a third neuron is in charge of modifying the intensity of the synaptic connection), the strength of the connections between sensory and motor neurons. A key neurotransmitter is serotonin, released by the interneurons of *Aplysia*, which affects the amount of glutamate that reaches the motor neuron from the presynaptic terminals of the sensory neuron.

Concerning long-term memories, the underlying molecular mechanisms seem to differ from those observed in the storage of short-term memories. Kandel and his team have discovered the presence of relevant genetic changes [15] that imply the participation of a regulating protein, CREB. Protein kinase A phosphorylates CREB, and this molecule activates a series of effecting genes in charge of codifying proteins that facilitate the formation of new and persistent synaptic connections. The process has been confirmed in *Drosophila melanogaster* [16] and it is highly probable that it constitutes the universal mechanism through which short-term memories are converted into long-term memories.

Investigations of this kind have certainly helped to pave the intellectual path that leads from molecules to mind [17]; even if a full molecular understanding of abstract thinking is still distant, the progress so far has been notable, a vivid proof of the power of science to unveil the unity of nature and the character of its fundamental rules.

From a broader perspective, it is now clear that experience and neural activity are capable of remodeling brain function. Even if the fundamental neuroanatomical structures of the brain remain stable, functional connectivity enjoys an extraordinary degree of plasticity. The equilibrium between structural stability and functional mutability is achieved through a process of constant regulation, in which nerve cells manage to produce consistent patterns of activity [18] that can be nonetheless reshaped in accordance with the new experiences accumulated by the subject. Thus, the genetically determined elements of the nervous system establish a set of feedback mechanisms with the environment, in a dynamic interplay between flexibility and stability that grants the human brain its remarkable levels of elasticity, adaptability and improvement.

The high specificity of many neurons is transmitted genetically, but the intensity of the connections can be altered, and in some cases new connections can arise. For example, Merzenich has proved the astonishing degree of plasticity exhibited by many sensory circuits, such that activity in adulthood can lead to their reorganization in the somatosensory and auditory cortexes. In consequence, acquired learning and the training of organs like the hand and the ear can have powerful effects on the cerebral cortex [19]. Of course, there are critical periods after which these effects vanish, but the intuition that habit and use reinforce and even expand certain capacities, whereas lack of use may result in the atrophy of an organ, has now been tested at a cortical scale [20]. Individual identity emerges as the fruit of a complex and fascinating exchange between genetics and environment, condensed in the transformation and creation of neuronal connections and neural maps. Hence, inherited information is reshaped by acquired information; behold the wonder of ontogeny, the beauty of individual development and its capacity to actively complement phylogeny.

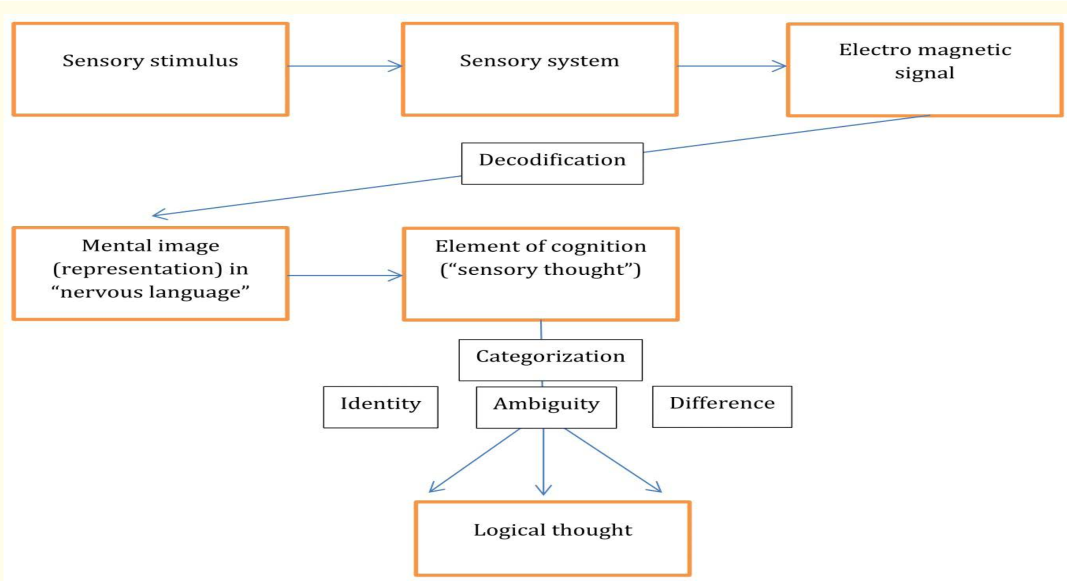
Towards an interdisciplinary understanding of consciousness

In any case, the importance of implementing an interdisciplinary endeavor is clear. No single discipline can manage the quantity and heterogeneity of information that surrounds the brain and the human mind. But an interdisciplinary approach, through the collaboration of branches of knowledge like biochemistry, genetics, neurology and cognitive science (a synthesis of approaches that defines the essence of modern neuroscience) [21], cannot hide the fundamental relevance of the chemical mechanisms upon which the operations of the brain are ultimately founded. As Changeux has written, “this creates a striking landmark in the thinking of brain sciences by causally and reciprocally linking the molecular to the cognitive levels both within the individual brain and between brains in the social and cultural environment, thus suggesting new bridges between brain sciences and humanities” [22].

In particular, the study of cellular communication, including the elucidation of the role played by chemical substances like neurotransmitters, is called to offer essential insights on how the different organizational systems of the brain exchange information. Hence, without the knowledge provided by the molecular level it will be virtually unfeasible to decipher the mysteries of an organ, the brain, capable of sharing vast amounts of information endowed with different degrees of complexity.

From a phenomenological point of a view, any model aimed at unifying the neurobiological and cognitive realms of the human mind has to pay attention to at least three essential elements: the perception of the external world, its assimilation by the subject and the conscious action derived from our thoughts and decisions (for the sake of simplicity, we will leave aside purely unconscious acts).

A potential explanatory model could be sketched in the following way:



For example, a sensitive signal with visual information is processed in the occipital lobe of the cortex. The mechanism runs according to Müller's law [23] of specific energies: the modality of a certain sense is a property of the sensory nervous fiber and each sense is capable of activating a specific stimulus. Thus, we do not enjoy direct access to the world and its objects, because our representation of reality is mediated by the specific modalities of the different senses and the way in which they process information [24]. In almost infinitesimal amounts of time -though the speed of nervous signals is not impressively high, as it is even lower than the speed of sound-, this information, encoded in electromagnetic language, travels through long-range connectivity from the posterior cortex to the prefrontal cortex (where pyramidal cells play a prominent role), not without being affected by the limbic system, the seat of processes of emotional nature. This emotionally encoded information moves forwards and upwards to the frontal cortex, first to the language-related areas and then to the associative regions of the brain. In the areas in charge of linguistic processing, the electromagnetic signal, which includes both the perceived stimulus and its emotional assimilation, becomes translated into an internal representation, channeled through the canons stipulated by a conventional language shared by the subject. The final processing in the associative areas of the prefrontal cortex facilitates an "independent" treatment of information, by allowing us to reflect on the information that has been apprehended.

The key to understanding consciousness lies in the synchronization of perception and association: the essential factor is time rather than space (location). There are, of course, specialized areas, but consciousness, the very human thought of which I am aware (not only a complex perception of the environment but a complex perception of the environment accompanied by the perception that it is me who is perceiving) involves a synchronization of this kind. As Buzsáki writes, "Neuroscience has provided us some astonishing breakthroughs, from noninvasive imaging of the human brain to uncovering the molecular mechanisms of some complex processes and disease states. Nevertheless, what makes the brain so special and fundamentally different from all other living tissue is its organized action in time. This temporal domain is where the importance of research on neuronal oscillators is indispensable, and it is this temporal domain that connects the work discussed in this volume to all other areas of neuroscience" [25].

If consciousness is intimately connected with time, the problem of the relation between the two poles of a binomial that has challenged most attempts at finding a synthesis points to the elusive correspondence between space and time, one of the mysteries about which our future physical knowledge will surely offer unsuspected conclusions. Language involves space (phonemes, their auditory aspect) displayed over time: a temporarily unfolded representation. Its effectiveness is sustained over a series of sound wave packets that are transduced into electrical impulses.

The so-called "binding problem" concerns the difficulty of understanding how it is possible for the brain, the recipient of sensory stimuli that are diverse in nature (visual, olfactory, gustatory, tactile ...), to achieve a unified representation. Another conspicuous difficulty, referred to *qualia* or secondary qualities, involves the subjectivity of certain experiences, a feature that is seemingly unavoidable for an objective explanation of the mind. However, both problems stem from an incomplete understanding of the nature of the mind. If we take into account the undisputable fact that any sensitive language is always translated into a code of electromagnetic impulses, the enigma of how to explain the unification of the various sensory stimuli in a unitary representation vanishes. Any piece of information is integrated into a single signal that forms the basis of my representation. In the case of visual *qualia*, a certain wavelength will pass through a specific neural circuit, whose structure will model which properties of the stimulus I will grasp and in which way (thereby generating a concrete sensation associated to each form of *qualia*). We are aware of something when we focus our attention on that object of thought. Only if we can filter the miscellany of stimuli arriving in our minds, emanated from the world or produced by our own subjectivity, we can acquire consciousness.

This admirable division of tasks, hierarchically distributed, dilutes the question of the ultimate instance of perception, decision or thought. Among the posterior zones (connected with perception), the emotional areas (the limbic structures in charge of assimilating information in their own way) and the associative regions of the brain a triangle is established, in a process of continuous feedback. In confronting a certain stimulus, we first react through a certain emotion that can be consciously filtered. But this purification is again sifted by the emotions that our mind generates. The tension between the perceived object, the stored emotion and the reasoning that tries to look for generalizations fosters a fruitful and fascinating reciprocity. Its creative power underlies some of the most outstanding achievements of the human mind, and it permits us to anticipate an answer to "Plato's problem" (as Chomsky has called it): "how we can know so much from such a limited range of experience" [26].

Consciousness is not a kind of holistic power that permeates space or mysteriously wanders through ungraspable dimensions, because there is no consciousness without object. Consciousness necessarily refers to an object: I am aware of the world, of myself, of my pain, joy and desires... I am aware of that which I know or ignore, but only if I pay attention to that object: my knowledge, my ignorance. However, we do not know whether consciousness requires a series of specific neurobiological structures or if it could exist in highly sophisticated artificial electronic circuits. No final argument prohibits that, in the not too distant future, a computer will be able to reproduce the internal world of our subjectivity through the correct elucidation of the electromagnetic code that sustains it. Of course, it would never exhaust this internal world, because it would never succeed -unless it had a potentially infinite power of calculation and integration- in imitating all the conditions (genetic, biographical, spatio-temporal...) that define our experiences, but the postulate of incommensurability between *qualia* and the objective dimensions of the universe seems to be unjustified.

Consciousness, in short, is language speaking with itself. If consciousness is closely linked to language, it is legitimate to believe that its semantic abilities resemble some sort of "syntax over syntax." As it is plausible to suppose that evolution has efficiently connected the Broca and Wernicke areas, this capacity to simultaneously coordinate syntactic and semantic talents may conceal the secret of human intelligence. We must remember that the concepts created by the mind juxtapose images in a hierarchical way, by highlighting those characteristics that have been more frequently observed and which we judge to be more relevant. A greater degree of biological complexity, as it in the case of our species, implies more possibilities of liberation from the constraints of bodily structures. Such a process favors increasing degrees of functionality, without being forced to satisfy a unique need that may absorb all our power. This expansion of versatility permits our biological structures to encompass multiple tasks, beyond a one-to-one relation between structure and function.

Conflicts of Interest

The author declares no conflict of interest.

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