

THE MULTIPLE MEANINGS OF «CEREBRAL COMPLEXITY»

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ABSTRACT: This paper discusses the difficulties of finding a rigorous and universal definition of «cerebral complexity». The main conclusion points to the necessity of accepting a creative tension between the quantitative and the qualitative dimensions of cerebral complexity.

KEY WORDS: Complexity; system; brain; quantitative; qualitative.

Los múltiples significados de la «complejidad cerebral»

RESUMEN: Este artículo examina las dificultades asociadas a la búsqueda de una caracterización universal y rigurosa del concepto de «complejidad cerebral». La conclusión principal apunta a la necesidad de aceptar una tensión creadora entre las dimensiones cuantitativa y cualitativa de la complejidad cerebral.

PALABRAS CLAVE: Complejidad; sistema; cerebro; cuantitativo; cualitativo.

1. THE CONCEPTS OF «COMPLEXITY» AND «SYSTEM»

It is often argued that the human brain is the most complex system known in the universe. Invoking cerebral complexity has actually become one of the principal tenets of many discourses that try to highlight the role played by this organ as the pinnacle of evolutionary development and the seat of our most outstanding cognitive abilities. However, it seems legitimate to pose the question about the meaning of complexity when it is referred to the brain. Is it indeed possible to propose a universal measure of complexity, and how would it affect our idea of cerebral complexity?

There are no universally accepted definitions of «system» and «complexity». Nevertheless, both concepts have acquired increasing importance in different fields of the natural and the social sciences. Intuitively, we can differentiate objects and systems of objects in terms of their complexity by focusing on, for example, the sophistication of its structure and the versatility of its functions. But when we seek to propose a more rigorous measure of complexity, we often encounter an almost insurmountable obstacle: the subjective nature of most of our valuations. Although the notions of system and complexity do not necessarily respond to purely subjective criteria, the perspective adopted by the researcher will greatly influence the meaning of these concepts and the conclusions that we can draw from them.

Notable attempts have been made at offering a more precise understanding of complexity, susceptible to quantification. For example, the algorithmic information content or Kolmogorov complexity of a binary string is defined as the length of the shortest program for a Universal Turing Machine (the mathematical tool equivalent to a digital computer) whose output is the given

string. Hence, Kolmogorov complexity measures the randomness of an object.

Intimately associated with this concept is the so-called «Shannon entropy», which plays a crucial role in information theory by providing a way to estimate the average minimum number of bits needed to encode a string of symbols, based on the frequency of the symbols. Shannon entropy permits us to quantify information (more specifically, the degree of uncertainty in a source of information) through an inspiring analogy with Boltzmann's classical definition of entropy. In highly simplified terms, it helps us determine the amount of information contained in a system, where information is viewed as the degree of order of the system. If a bit is the unit of information, susceptible to adopting two values (0 and 1), we can define the information size of a set A as the number of bits that are necessary to encode each element of A separately. The entropy is defined in terms of the probability. A very probable element contributes with little information to the system, because it will not differ significantly from our average expectations and our previous knowledge. This concept of information is therefore opposed to that of entropy, which measures the degree of disorder of the system. Since order is thermodynamically less probable than disorder, higher levels of order will mean lower levels of entropy and hence higher levels of «valuable» information.

Other definitions of complexity have been proposed in recent decades, like the Lempel-Ziv complexity, the logical depth of Bennett, the effective measure complexity of Grassberger, the complexity of a system based on its diversity, the thermodynamic depth, the ϵ -machine complexity, and the physical complexity of genomes. The criteria used for characterizing the complexity of an object or process are generally grounded upon factors the difficulty of description, the difficulty of creation and the degree of organization of a system [for an overview, see 1].

A model that relates information and complexity within a framework of interest for the cognitive sciences is the so-called «integrated information theory» (IIT) [2]. This model has attracted considerable attention, given its promising explanatory value for a theory of consciousness and its potential ability to justify why some neural mechanisms instead of others are associated with subjective experience. Resting on a series of axioms and postulates susceptible to mathematical formalization, a key component of the model is ϕ , a magnitude that measures the degree of integration of a particular information. High values of ϕ mean that information possesses a high degree of differentiation from other pieces of information and that it is the result of a recurrent, hierarchical connectivity. As Tononi writes, «in IIT the information content of an experience is specified by the form of the associated conceptual structure (the quality of the integrated information) and quantified by Φ_{\max} (the quantity of integrated information). In IIT, information is causal and intrinsic: it is assessed from the intrinsic perspective of a system based on how its mechanisms and present state affect the probability of its own past and future states (cause-effect power). It is also compositional, in that different combinations of elements can simultaneously specify different probability

distributions within the system. Moreover, it is qualitative, as it determines not only how much a system of mechanisms in a state constrains its past and future states, but also how it does so. Crucially, in IIT, information must be integrated. This means that if partitioning a system makes no difference to it, there is no system to begin with. Information in IIT is exclusive—only the maxima of integrated information are considered». [3] These features show that the concept of information used by IIT differs from Shannon information in significant ways: «Shannon information is observational and extrinsic—it is assessed from the extrinsic perspective of an observer and it quantifies how accurately input signals can be decoded from the output signals transmitted across a noisy channel. It is not compositional nor qualitative, and it does not require integration or exclusion.»

Nevertheless, by insisting on the integrated nature of conscious information this model may eclipse another important and defining feature, namely the necessity of distinguishing the content of one element of information from another in order to become conscious of it. Indeed, it seems that the subject has to «judge» the information as an external observer in order to acquire consciousness of it. Moreover, the character of conscious experience is not clarified in a satisfactory way, because information can achieve high degrees of integration through non-conscious processes.

For our purpose, which is to gain an intuitive understanding of complexity that can be useful for evaluating cerebral complexity, Shannon entropy is important. Nevertheless, it does not encapsulate some relevant aspects of the inherent complexity of a system. We cannot be sure to have grasped the full potential of the idea of complexity by simply examining the amount of valuable (i.e. specific) information stored in a system. One of the reasons lies in an intrinsic difficulty connected with the idea of information. Although this notion is of great importance for any scientific analysis, it is not clear that even Shannon entropy is capable of offering an objective and universal definition of information. An element of reality can be of informative value for one species while being of no utility for another species. It therefore seems inexorable to take into account the role played by the agent in charge of interpreting a certain piece of information. If information does not necessarily entail intrinsic value (independent from the judgment of a particular species or subject), how can we feel legitimate to grant it a more prominent role in our quest for a universal definition of complexity? Everything is susceptible to being contemplated as an expression of information: an electron, a boson, an atom, a planet... Nevertheless, this insufficiency does not preclude the incorporation of some interesting insights that can be drawn from the theoretical study of information, as we shall discuss.

Likewise, if in order to define complexity we have to rely upon distinctions between, for example, random and non-random elements in the system, it is difficult to attain a fully objective description, in which all subjective biases have been completely eliminated. Thus, in most cases it is the observer who interprets the value of the data in accordance with his own model, thereby

introducing a subjective judgment that may not be shared by all potential observers. The margins of subjective interpretation may perhaps be minimized as to objectivize our description of complexity through a series of rigid factors, capable of diminishing the number of degrees of freedom within our model. Yet, it is difficult to assert that any distinction based upon the observer's judgment can be completely eliminated, even if it may be circumscribed to the minimum and sufficient number of elements of judgment that reduce the separation between the quantitative and the qualitative dimensions.

The previous reflections on complexity need to be complemented with an examination of two essential conceptual preliminaries: the ideas of *system* and *model*.

From an intuitive point of view, a system can be contemplated as an arbitrarily separated portion of reality (like a physical system) or thought (like a conceptual system) in which the parts establish interactions that prevent us from understanding them in isolation. The brain would certainly satisfy this definition. Its architecture assembles a set of elements (neurons, glial cells...) where the activity of its individual components, both mutually homogenous (like one sensory neuron in relation to another) or mutually heterogeneous (like one motor neuron in relation to one sensory neuron), can only be comprehended by taking into consideration their role as parts of a larger unity (a cortical area or, moreover, the brain as a whole). And generically, we can regard the complexity of a system as the type of behavior characterized by a high number of possibilities in combining its elements. This understanding of complexity is merely quantitative. Nonetheless, we can include the qualitative dimension by realizing that this high combinational power can also be translated into an equally high degree of initial indeterminacy of the system (or «degeneracy»), given that the larger number of possibilities of evolution makes it more complicated to predict the exact behavior that the system will exhibit in the future.

A model can be understood as the description of a system or set of systems in which certain elements taken from a domain of reality are organized through primitive notions, explanatory principles and relations of logical inference. Thus, a more complete model is that which reproduces reality in a 1:1 correspondence, thereby minimizing the number of elements of reality that are not contemplated by the model (in terms of its extension) and grouping these elements into a set of basic principles (in terms of its «intension»). A model of an object or process can therefore be regarded as an elucidation of its fundamental, defining elements and principles.

2. QUANTITATIVE COMPLEXITY AND HETEROGENEOUS INFORMATION: A CREATIVE TENSION

It is not difficult to find examples of surprisingly complex systems in the universe. If we think of the solar system, which consists of a star, eight planets, one hundred and seventy-five natural satellites, asteroid belts, comets, and

cosmic dust, it is clear that an astonishingly high degree of complexity will emerge. For example, as soon as we intend to isolate, within this system, a subsystem constituted by three bodies and we try to determine their motions departing from an initial set of data regarding the positions and the momenta, we succumb to a famous longstanding problem of the physical sciences, the so-called «three-body problem», for which an analytical solution does not seem possible. Thus, even in an astrophysical system composed of three bodies interacting through gravitational forces it is impossible to obtain an analytical determination of their positions and velocities at any instant.

Also, if we address the question about the complexity of the solar system from the atomic level and we try to imagine the approximate number of existing atoms, the figure will exceed by far the number of neurons in an average human brain (and the number of cortical neurons is for many scientists a direct measure of the cognitive abilities of a certain species [4]). To a first approximation, we can use Avogadro's constant to calculate the number of constituent particles contained in a certain massive object. For the sake of simplicity we can establish a direct relationship between the mass of an object and the amount of information —measured in terms of the amount of molecules— that it stores. In system like the solar system, if we approximate its mass by taking into consideration the mass of its largest object —the Sun—, which is equal to 2×10^{33} g, we obtain 1.2×10^{57} atoms. Indeed, this is a vast amount of information, a value indisputably much higher than the average 8.6×10^5 neurons in the human brain [5] (in molecular terms, the number of neurons would only grow by some orders of magnitude).

Of course, the complexity of the brain depends not only on the number of its neurons but more importantly on the number of synaptic connections that they can form. Thus, another possible approach to the problem would be to calculate the number of potential combinations allowed by the neurons and synapses that exist in an adult brain. However, even if we take into account the average 10,000 synapses per neuron and the vast number of glial cells (c. 10 times the number of neurons), the orders of magnitude are still relatively low compared to many physical systems. This quantity would not be substantially increased if we examined the total number of brains interacting in a human civilization.

Hence, from a purely quantitative angle we cannot accept the idea that the human brain is the most complex system in the universe. It will always be possible to find quantitatively more complex physical systems, even if we ignore the nature of their internal dispositions and the versatility of their combinations. In fact, we have acquired a more complete understanding of many biological phenomena —*prima facie* blessed with higher degrees of complexity— than of some physical phenomena. There are processes in the field of fundamental physics that we have not yet managed to understand even remotely (the ideal of completeness should be certainly regarded as an asymptotic limit, as a noble but utopian goal). Indeed, current mysteries such as the measurement problem in quantum mechanics may be more complex than many unsolved questions of biology.

In this way, absence of understanding and abundance of analytical difficulties cannot emerge as sufficient factors for attributing complexity to a system. We do not understand the finest details of atmospheric weather as to predict it several weeks in advance, but we adhere to the conviction that this system is far less complex than the human brain. Of course, the accumulation of factors involved in shaping the weather confers an almost unlimited degree of complexity to this system, but this is also the case with the human brain. If we believe that it is too complex to calculate the interactions of countless gas particles in the atmosphere, will there not be even more interactions between the particles of the brain, which are also in constant exchange with the environment and themselves?

It therefore seems that we must pose a *qualitative* question. Any reference to the qualitative dimension may generate suspicion, because of its potentially subjective character. However, it is inevitable for human understanding to distinguish between the quantitative (the number of elements that constitute a system) and the qualitative dimensions (the different forms of configuration that these elements present).

When we explore the biological kingdom, the qualitative dimension is often inescapable. The purely quantitative aspects do not suffice for defining the exuberance and complexity of organic forms, their ability to adapt themselves to mutable environments and their power of variation, given the importance of the qualitative dispositions of their material elements. A system like the DNA double helix may seem enormously complex from a quantitative point of view, and it certainly is. However, from a physical-chemical perspective the complexity of the double helix is remarkable, but not impressive. In fact, progress in the biological sciences has granted us an extraordinary degree of clarity and depth in our knowledge of the deoxyribonucleic acid. This feat would have been inconceivable if the system were so quantitatively complex as to defy any attempt of scientific elucidation. The truly striking features point not so much to the number of elements involved in the system but to their capacity of combination, to their functional versatility. Thus, its most outstanding feature lies in the astronomical combinatorial capacity of its nitrogenous bases. To give an example, in the genome of *Homo sapiens*, where we find approximately 5.6×10^5 pairs of nucleotides, it is possible to obtain the vast amount of $4^{5.6 \times 10^9}$ different DNA sequences. Variability, understood as the possibility of structuring information in different modes, therefore rises as an essential element for the development of complexity in living organisms.

The interplay between the amount of information stored by the system and its heterogeneity (or difficulty to fit patterns of order that can be clearly defined in accordance with previous information) offers an interesting point to view for dealing with cerebral complexity. Heterogeneity can be defined through statistical categories like «distance from equipartition». However, the notion of «heterogeneous information», meaning a certain degree of distance from equipartition, implies that complexity cannot be measured in absolute but in relative terms, as compared to other systems. Then, it should be treated

as a statistical description of the system at a given scale, which stems from probability distributions [see 1]. In essence, conceptually we are taking into consideration the amount of information (measured according to Shannon entropy) and the amount of new patterns needed to encapsulate this information: its quantity and its quality (i.e., heterogeneity). A star can store vast amounts of information in terms of the elementary particles and processes that take place inside it, but the information involved is essentially homogeneous. In the human brain, in spite of the homogeneity of many neurons, glia, and synapses, the organizational asymmetries introduce a high degree of heterogeneity, or distance from an equiprobabilistic distribution.

Higher degrees of order—and hence lower levels of entropy—imply that the system is more predictable. Likewise, a highly disordered system, refractory to predictability, offers more distinctive information than a highly ordered one. The reason is that its array of elements and properties cannot be simplified into a general rule, capable of comprising the existing information through the repetition of a certain sequence. In consequence, it turns to be more difficult to specify the state of the system in light of its past states.

Of course, this view suggests that complexity should be understood as the amount of information required for specifying the state of the system. Hence, this category would reflect the complexity of the underlying mechanism (by a mechanism we mean the elucidation of the spatial and temporal sequence which, from an arbitrarily fixed point of departure to a convened point of arrival, contains the necessary and sufficient information about the elements of reality involved in that particular situation—that is to say, a sequence of steps mediating between an initial and a final state—).

Nevertheless, the previous definition does not seem to grasp the deepest nature of cerebral complexity, at least if we compare it to the complexity that can be discerned in many physical systems. We cannot specify the state of a quantum system with absolute certainty, and even if we decide to disregard quantum mechanics (due to the epistemological difficulties that it poses), we still face the problem that many physical systems—which *a priori* appeared to be less complex than the human brain—demand a vast amount of information if we want to specify their present state.

Furthermore, it is necessary to realize that despite exhibiting a more «heterogeneous» nature, a highly disordered system may be so chaotic that actually no valuable information can be extracted from its analysis. Therefore, it seems legitimate to argue that it is in the interplay between order and disorder, between low and high entropy, where a reasonable approach to the nature of complexity can reside. If every element were independent from each other—thereby constituting a completely random entity—, we might perhaps contemplate a large amount of information deprived of order, but the value or «quality» of this information would still be low.

From this perspective, complexity suggests a creative tension between order and disorder, between a set of patterns and rules and the absence of a clearly discernible organization. Thus, although the difficulty in subsuming

the properties of the system into a general rule or set of patterns sheds light on its level of complexity, it does not stand as a sufficient criterion if we want to distinguish, for example, the complexity of atmospheric weather from cerebral complexity. After all, it is inevitable to invoke the nature of the system's functions in accordance with our own method of valuation. We hold in higher esteem the properties of the brain than those exhibited by a very unpredictable system like atmospheric weather because of the abilities that they manifest.

Hence, it is not only a matter of functional heterogeneity but of the intrinsic nature of a certain capacity possessed by the system. Through abstract thinking and our highest cognitive abilities, we are able to encompass a vast range of phenomena into our conceptual models or representations of the world. Perhaps it is in this power to design broader models of reality, which by compressing potentially infinite amounts of information into concepts offer the possibility of condensing vast amounts of heterogeneous information into a set of explanatory tools, where the true complexity of the human brain resides. A more universal model of reality can be regarded as a more objective representation of the world, given that it allows us to unify a multiplicity of elements, far too distant from our ordinary perceptions and subjective experiences. This higher degree of order, which operates through the identification of general rules, is at the same time a simplification of the world, aimed at encompassing diversity into unity.

Along these lines, the triumph of the natural sciences in their effort to discover patterns of activity in the physical world corroborates both the efficiency of our model of the universe and its flexibility for exploring new categories, sometimes unquestionably remote from the ordinary range of experiences to which the average human being has access. This exchange between order (seen as explanatory efficiency) and disorder (understood as creative imagination) seems to be the true seal of our cognitive complexity. It grants us the possibility of contemplating at the same time the simplicity and the intricacy of the surrounding world, thereby proposing an evocative signature of the sophistication of our mental models of reality. In fact, a cognitive scale of complexity could be constructed by examining the quantity and the quality of the information about the universe that a certain species can assimilate.

In this way, a potential characterization of complexity that is consistent with our previous line of thought points to the difficulty of reducing an object or process to the more fundamental levels of explanation that are known to us. A reality can be described as «more complex» if in order to understand its structure and function one needs to add new explanatory principles that are absent in the description of the more fundamental levels of reality upon which it rests. Hence, biological systems and cognitive processes are intrinsically more complex than elementary inorganic physical systems, because even if presently one normally employs less abstract and formalized conceptual tools to describe them than in the field of fundamental physics—with its highly abstract mathematical language—, their depiction involves, in addition to the same elements and principles than in basic physical systems, new explanatory tools that are exclusive to this domain of reality.

At this point it may be useful to invoke certain ideas whose fruitfulness has been proven in the domain of other sciences, like cultural anthropology. In particular, Leslie White's thesis that the degree of development of a particular culture lends itself to description and interpretation in terms of the quantity and quality of the energy needed by this human group provides a fertile way of judging the complexity of a biological entity [see 6]. The use of energy («the capacity to perform work»), both in its quantitative and qualitative aspects, mirrors the complexity of the structural and functional organization of a certain creature. Of course, important cultural elements like symbols, relations of power, spiritual values, and cognitive development do not establish a simple, 1:1 correspondence with the energetic infrastructure and the concomitant enhancement in productivity. Likewise, analyzing the complexity of a biological entity from the point of view of its quantitative and qualitative capacity for processing energy only provides a general perspective; yet, it does not exhaust the understanding of many specific behaviors that are not strictly determined by the available energy. For example, we should notice that there can always be «degenerate states», meaning structural and functional manifestations that could be obtained from the same energetic infrastructure, thus reflecting possible different outcomes from the same input. Also, we must insist that a purely quantitative assessment of the energy used by an entity does not help us distinguish the complexity of the solar system from the instantiations of biological complexity.

In neuroscientific terms, the type of complexity that seems to be relevant for our purpose is associated with the number of stages in the evolutionary development of a system. Natural selection had to act upon a greater amount of genetic variations, and its influx had to be sustained throughout a longer number of generations, in order to gradually filter those changes that offered adaptive advantages. Likewise, it could be argued that the birth of a system such as the human brain, which demanded a myriad of evolutionary stages, was less probable than the emergence of other biological systems. This perspective would allow us to consider the human brain as an unquestionably more complex system than virtually all other known biological organizations. However, it is conceivable that an equal or even higher number of evolutionary stages and an equal or even higher number of sustained genetic variations might have produced a much less complex organ. There is no clear causal relationship between the extension of the evolutionary path and the complexity of the result, because some itineraries could imply regressions to less complex biological forms if adaptive pressures were to favor this footway.

Another criterion for assessing cerebral complexity might invoke the relative size of our brains when compared to other species'. As Gazzaniga writes, «we have brains that are bigger than expected for an ape, we have a neocortex that is three times bigger than predicted for our body size, we have some areas of the neocortex and the cerebellum that are larger than expected, we have more white matter» [7]. Both the absolute and the relative sizes (as measured by the encephalization quotient) of our brains would help us evaluate their complexity [8]. However, compelling it may seem, this explanation only illuminates the

relative complexity of the human brain, but it leaves aside a robust measure of its potential inherent complexity. Moreover, it does not clarify much about the complexity of cerebral functions (the «qualitative complexity» that we have mentioned earlier), as it merely indicates certain quantitative features [9]. This failure would corroborate the impossibility of defining cerebral complexity as an intrinsic measure of the system, regardless of its ratio to other systems.

Thus, a reasonable way for assessing the specificity of a highly complex system like the human brain (the seat of our mental capacities) may point to the range of actions that it is able to display. This possibility is rooted in the level of quantitative complexity that the system possesses, but this is not the only factor that needs to be considered. It is upon the typology of the connections—and therefore on a subtler and deeper realm of analysis—that the qualitative complexity is based.

CONCLUSIONS

In conclusion, it seems difficult to liberate the concept of complexity from any reminiscence of subjective valuation. We believe that the human brain is the most complex system of nature because it represents the known basis of the most distinctive cognitive abilities of the human species, the organ that opens us to a vast range of tasks and unique possibilities whose detailed scientific explanation is in principle more elusive than that of other structures and functions in the universe.

Although subjective and based upon our perception of the value exhibited by some of our behaviors, this opinion does not seem to be completely misleading. Abstract thinking projects us to a class of operations that allow us to acquire a much more universal and profound perspective about the universe by elucidating its fundamental laws. Therefore, it is in the type of functions enabled by a system where we may contemplate the most revealing criterion for establishing a hierarchy of complexity, at whose summit the human brain would be enthroned. Again, this degree of functionality is intimately connected with the quantitative substrate that supports it. However, in the evolution of organic forms we witness a progressive decoupling between structure and function. The interplay between analogous structures—sometimes endowed with relative simplicity—, combinatorial art, selective stabilization, and an efficient genetic program offers the possibility of displaying a much more exuberant and sophisticated range of actions. Evolution has not needed to innovate in many of the fundamental molecular mechanisms in order to develop features like the functionality of the nervous system and the basic neurobiological mechanisms underlying the transmission of the nervous impulse. Although the human brain enjoys extraordinary structural complexity, the functional complexity that it manifests is even more admirable and intriguing. It is in the number of viable combinations and in the efficiency achieved by them where this functional complexity can be legitimately emphasized.

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