Understanding the brain

How can our intuition fail so fundamentally when it comes to studying the organ to which it owes its existence?

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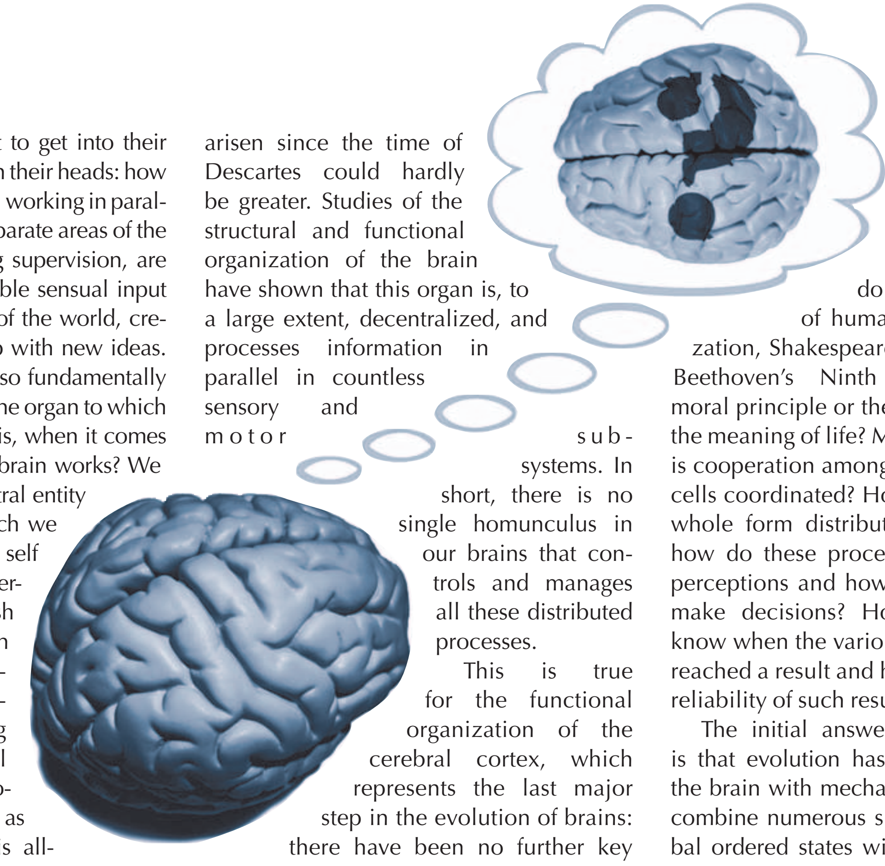

People find it difficult to get into their heads what goes on in their heads: how billions of nerve cells, working in parallel on individual tasks in separate areas of the brain with no coordinating supervision, are nevertheless able to assemble sensual input into coherent perceptions of the world, create decisions and come up with new ideas. How can our intuition fail so fundamentally when it comes to studying the organ to which it owes its existence—that is, when it comes to understanding how the brain works? We imagine that there is a central entity at work in our heads, which we equate with our conscious self and that has all the wonderful abilities that distinguish us as humans. This intuition imposes itself so persuasively—even overwhelmingly—that it is not surprising that, throughout our cultural history, scientists and philosophers have speculated as to where in the brain this all-powerful and all-controlling entity might be.

The plausible assumption was that there must be a single location where all information about our internal conditions and environment is made available, decisions are taken and actions are initiated. Even Descartes—who considered mental processes to be superior to, rather than connected to, material processes in the brain, and whose free-floating *res cogitans* would therefore have needed no circumscribed location—did not believe that it was possible to get by without a singular localizable controlling entity.

The contradiction between this assumption and the scientific evidence that has arisen since the time of Descartes could hardly be greater. Studies of the structural and functional organization of the brain have shown that this organ is, to a large extent, decentralized, and processes information in parallel in countless sensory and motor subsystems. In short, there is no single homunculus in our brains that controls and manages all these distributed processes.

This is true for the functional organization of the cerebral cortex, which represents the last major step in the evolution of brains: there have been no further key structural innovations since it first appeared in lower vertebrates. The volume of the cortex has grown continuously over the course of evolution, which has drastically increased the complexity of its networking possibilities, but the internal connections between the new areas are identical to those found in lower vertebrates. The progressive differentiation of cognitive activities is therefore based primarily on an enlargement of the cerebral cortex. Its invention is apparently one of the greatest achievements of evolution: an information-processing entity that handles all the manifold and diverse tasks that higher organisms with complex behaviour and social systems must manage.

However, if there is no central entity operating at a higher level, how do we explain the rise of human culture and civilization, Shakespeare's *Romeo and Juliet*, Beethoven's Ninth Symphony, Kant's moral principle or the quest to understand the meaning of life? More specifically, how is cooperation among the many billions of cells coordinated? How can the brain as a whole form distributed activity patterns, how do these processes create coherent perceptions and how does such a system make decisions? How does this organ know when the various subprocesses have reached a result and how does it assess the reliability of such results?

The initial answer to these questions is that evolution has obviously equipped the brain with mechanisms that allow it to combine numerous subprocesses into global ordered states without a central coordinating entity. However, we are still far from understanding the principles by which distributed processes in the brain assemble into coherent states that then act as the substrates of perception, concepts, decisions and actions.

One hypothesis centres on the problems that occur when the brain processes visual signals. Owing to their specific interconnections, nerve cells in the visual cortex of the brain react selectively to elementary features of visual objects, such as contours, textures, colour contrasts and movements. Neurons at higher processing levels then respond to combinations of these elementary features. Initially, this led to the idea that the association between elementary features and representations of entire objects was achieved by cells at the highest level of the processing hierarchy, which respond selectively to particular constellations of individual objects and their features.

So, for every perceivable object, there should be a specialized nerve cell in the visual cortex that signals the existence of this object; however, it was never possible to confirm this experimentally. In fact, nature chooses this option only in exceptional cases at best—specifically to represent frequently occurring or meaningful objects. Otherwise, this strategy would require an astronomical number of highly specialized cells to represent all perceivable objects in their various forms. It would also mean that we would be incapable of perceiving objects that humans have never seen before, as this would imply the unimaginable possibility that evolution was provident enough to create appropriately specialized cells.

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In fact, highly developed brains use a more flexible strategy. They represent objects of perception—whether sensed visually, acoustically or tactilely—through many simultaneously active neurons, which individually encode a partial aspect of the whole.

The neuronal counterpart of any object therefore consists of a spatiotemporally distributed excitation pattern in the cerebral cortex, produced in each case by numerous cells. Similarly to the way in which a limited number of letters yields a vast collection of words and sentences, the recombination of neurons, each of which encodes individual elementary features, makes it possible to represent an infinite number of objects—even those that we have never seen before. However, this strategy requires that the excitation pattern relays two messages at once: the neurons must report that the special feature they encode is present in the field of view, and they must also indicate with which other neurons they are currently cooperating.

More than a decade ago, scientists discovered that neurons in the visual cortex can synchronize their activities with a precision of a few thousandths of a second, usually generating rhythmic oscillations at a frequency of around 40 Hz. This was followed by the important observation that nerve cells, particularly when they are co-involved in encoding a single object, synchronize their activity. These observations led to the conclusion that this precise synchronization of neuronal activities, for which cells have temporarily joined to form functionally coherent ensembles, represents the neuronal signature of a given object.

As is so often the case, the original discovery merely uncovered the tip of an iceberg. It is now becoming clear that the neuronal synchronization phenomena are far more important. In the years after the discovery of synchronous oscillatory responses in the visual system, an increasing number of laboratories has used multi-site recordings of neuronal activity to investigate the temporal coordination of distributed neuronal responses. This has revealed that the oscillatory pattern of neuronal activity and the synchronization of rhythmic discharges are ubiquitous phenomena in the nervous system, and, with all likelihood, are involved in many cognitive and executive functions. This indicates that synchronization facilitates signal propagation in neuronal networks with sparse connectivity, such as the cerebral cortex. Moreover, recent data indicate that synchronization of oscillatory activity selectively facilitates the exchange of information between cortical regions that oscillate in the same rhythm (Singer *et al*, 2007).

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These findings have led to the conclusion that synchronization can be used: to define, with high temporal precision and flexibility, the relationships between distributed responses, and to bind them together for further joint processing; to select responses for further processing; to support the selective routing from sender to receiver within distributed networks; to bind responses from different sensory subsystems into coherent representations; to establish connections between sensory and executive structures; to maintain contents in working memory; to strengthen associations between synchronously active cell assemblies by synaptic plasticity; and to support the formation of activity patterns that have access to conscious processing.

The findings of recent studies on patients with schizophrenia have yet another—possibly even more exciting—implication: that the synchronization of neuronal activities in these individuals is flawed and imprecise (Uhlhaas *et al*, 2006). If synchronization does in fact coordinate neuronal operations that are spatially distributed and that take place in parallel, it would explain some of the dissociative phenomena that characterize this puzzling disease.

Regardless of how we explain the diverse coordination problems in our decentrally organized brains, one thing is already clear: the dynamic states of the many billions of linked and interacting neurons in the cerebral cortex reveal a degree of complexity that surpasses anything we can imagine. This does not mean that we cannot or will not develop analytical methods to identify these system states and to track them chronologically; however, the descriptions will be abstract and vague, and will bear no similarity to our familiar perceptions and concepts that are based on these neuronal states.

To our intuition, it seems alien that the neuronal correlate of what we perceive as a solid tangible object is a highly abstract, spatially and temporally structured excitation pattern, and that not only three-dimensional objects but also smells, feelings and intended actions are represented in this way. Moreover, every such representation corresponds to one of a vast number of possible states, or, to put it differently, the cerebral cortex system continuously moves from one point to the next in an inconceivable multidimensional space. This trajectory—that is, the trail of this movement—depends on the entirety of all internal and external factors that have an impact on the system.

During its progression through this multidimensional state space, the system continually changes because its functional architecture is constantly altered by the experience it gains along the way. Therefore, it can never return to the same location. This explains why we experience time as irreversible. The second time we see a certain object, it affects a different dynamic state to the first time; we recognize it as being the same object, but the new state also reflects the fact that we have seen it before.

These deliberations hint at the abstract descriptions we will need to gain a deeper understanding of the processes that take place in the brain. This brings us back to the question of why our imagination is so ill-suited to understanding these processes in the brain and, therefore, its own foundations.

This inability is presumably caused by our limited cognitive abilities, which evolved in a world in which there was no advantage to be gained by understanding nonlinear complex multidimensional processes. The dimensions of animals with a nervous system range from millimetres to a few metres, and their cognitive and executive functions have adjusted accordingly to compute interactions between objects of this magnitude. The world as we perceive it is governed by the laws of classical physics that describe solid bodies, causal interactions, and absolute coordinates of space and time, which are sufficient for understanding most processes that are important to us. Presumably for that reason, the laws of classical physics were discovered before the laws of quantum physics.

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However, as with quantum mechanics, we can indeed observe processes that contradict our concepts of causality and linearity, although we find it difficult to grasp intuitively the laws behind them. The reason why we are so inept at imagining nonlinear interactions might be that, as living beings, this ability would have been of little advantage to us. After all, organisms benefit from creating models of the world only if these models allow them to make accurate predictions. In highly nonlinear dynamic systems, this is not possible; their future development cannot be predicted, even if all the starting conditions are known. So, there would presumably be no selective pressure for the development of cognitive functions that allow us to comprehend nonlinear dynamic processes.

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This limitation of our cognitive skills could explain why our intuition has developed ideas about the organization of our brains that are at odds with the scientific descriptions of this organ. If we assume that our brains operate in the same way as linear systems—such as the way a clock works—we must also assume that a creative mover interferes with this system to endow it with properties such as openness, creativity, intentionality and limited predictability.

However, in complex, nonlinear and self-organizing systems, these properties emerge naturally from the dynamics of the system and need not be invoked by an additional conductor. The human brain undoubtedly constitutes the most complex system in the known universe—here, ‘complex’ does not mean simply complicated, but instead designates specific characteristics of a system comprising many individual active elements that interact in special ways. Such systems can produce qualities that are creative and cannot be derived from the characteristics of the components alone: they can take on a vast number of states in multidimensional spaces to create new unpredictable patterns.

So, why did evolution create brains with these properties when they are primarily concerned with analysing linear processes? The answer to this question must—at least for the time being—remain incomplete because we are just beginning to understand the organizational principles of our brains. It is becoming clear, however, that evolution was counting on the particular flexibility of complex nonlinear systems. After all, they can come up with much more elegant solutions to problems in information processing than can linear operations—for example, by recognizing patterns, forming categories, associatively linking large quantities of variables and making decisions.

The ingenious trick is to transpose the low-dimensional signals from our sensory organs into high-dimensional states, to process them in this state and then to transform the results back to the low-dimensional space in which behavioural reactions occur. It is interesting that we have no insight into the high-dimensional nonlinear processes in our brains and perceive only the low-dimensional results. That is why we imagine that the same linear processes that we attribute to the observable phenomena in the world also take place in the brain—and that is presumably the reason why we believe that there must be a central control entity at work in our brains.

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Linear systems cannot organize themselves. They are not creative. They move in unchanging circles, and creating a new system therein requires external manipulation—a mover. Because we assume linearity, but experience ourselves as creative and intentional, our intuition leads us to the false conclusion that there must be a higher controlling entity in our brains that coordinates all the various distributed processes and creates impulses for new ideas. Moreover, as we are incapable of grasping this virtual entity, we ascribe to it all of the immaterial attributes that we associate with the concept of self—namely, the abilities to have initiative, to want something, to decide and to invent.

This speculation might serve as a warning whenever we interfere with the dynamics of complex systems, whether intentionally or out of necessity. Most areas of the living world that comprise numerous active and interacting components are complex systems that exhibit highly nonlinear dynamics—from social and political systems to financial markets and biotopes. By acting, we inevitably become active components of these systems, and our actions promote their dynamics and future development.

This confronts us with a serious problem. Because we lack the intuition to understand nonlinear behaviour and therefore focus primarily on linear models, we tend to underestimate the capacity of these systems to self-organize, but at the same time overestimate our ability to control them. As a consequence, we assume that the most effective strategy for stabilizing and controlling these systems is to establish central entities that regulate the distributed processes and steer the system in the desired direction. A glance at the hierarchical structures in our social and economic systems suffices to demonstrate that we are only too willing to follow this intuition and to put it into action.

But this raises the question of whether we can trust these central regulatory entities and whether we overestimate them by expecting more than they are able to deliver, even under optimal conditions. For fundamental reasons, the development of complex systems is open and difficult to forecast, even when the starting conditions are fully known. For the same reasons, it is difficult to foresee how any intervention or control will affect the behaviour of a complex system.

Under these circumstances, it is prudent to investigate carefully the dynamics of the respective system before installing institutionalized control mechanisms. If it is a straightforward system with primarily linear dynamics, then hierarchical structures might be appropriate. If, however, the system is highly complex with strong nonlinear behaviour, then we should rely on its self-organizational power and creativity, and not succumb prematurely to the illusion that we can selectively intervene. In this case, it is advisable to structure interactions and information flows in such a way that the self-organizing mechanisms can develop optimally.

Nevertheless, it is good news that the systems we encounter in the living world were able to develop to their state of high complexity but remain tolerably stable. It should encourage us to trust more in their robustness and their ability to self-organize: no planner, however astute they might be, could ever have designed systems that are as complex as the human brain or our social structures, or have done so in such a way that they would work and remain stable over such long periods.

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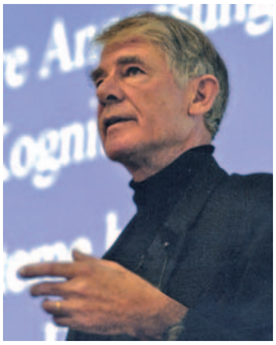

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