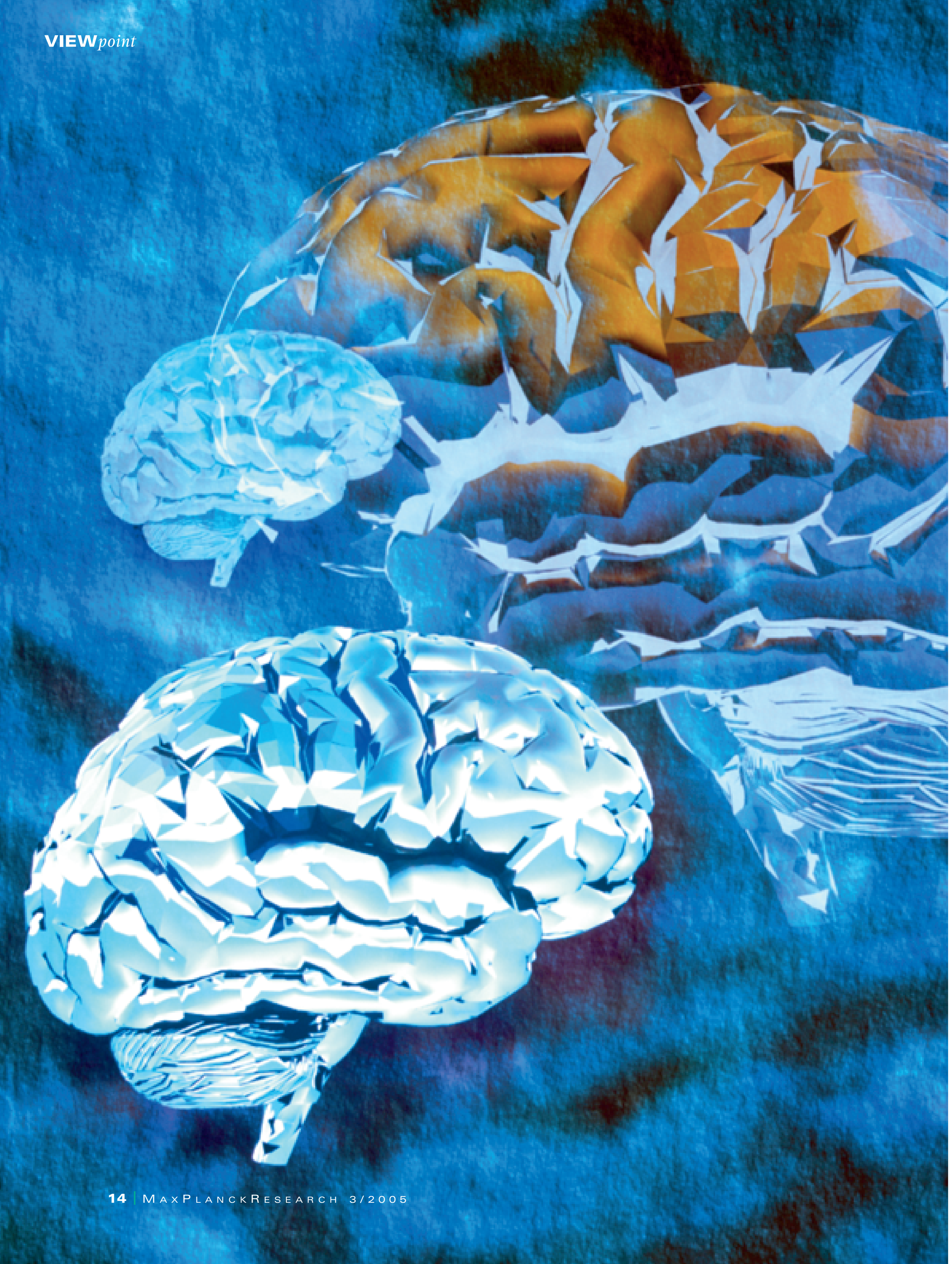


The Brain – An Orchestra without a Conductor

People cannot really get into their heads just what goes on in their heads: billions of nerve cells work on their individual tasks in separate areas of the cerebral cortex with absolutely no coordinating supervision – and nevertheless convey coherent perceptions of the world as discerned by our senses. **WOLF SINGER** *describes how this principle works and provides insight into the most complex and fascinating structure in the material world.*

How can our intuition err so fundamentally the moment it comes to studying the organ to which it owes its existence – when it tries to fathom how our brain is organized? If we turn our gaze inward, we imagine at work in our head a central entity that we equate with our conscious self and that possesses all the wonderful capabilities that distinguish us as humans. This intuition imposes itself so persuasively – even overwhelmingly – it's no wonder that there has been so much speculation throughout our cultural history about where in the brain this all-powerful and all-controlling entity could be domiciled.

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

The contradiction between this concept and the scientific findings that had since become available could hardly be more drastic. Studies of the structural and functional organization of our brain have shown that this organ is organized, to a great extent, decentrally and distributively, and that countless different processes take place in it in parallel in sensory and motor subsystems – and that there is no single center that manages these multifaceted processes.

This is particularly and impressively evident from the functional organization of the cerebral cortex, which constitutes the last major step in the evolution of brains: there have been no major structural innovations since it first appeared in the lower vertebrates. The volume of the cortex grew continuously over the course of evolution, causing also the complexity of networking possibilities to increase dramatically, but the internal connections between the new areas are identical to the old ones. The progressive differentiation of cognitive activities is thus based primarily on a quantitative proliferation of cerebral cortex – the invention of which is apparently one of evolution's great achievements: the

ILLUSTRATION: CORBIS

realization of an information processing principle that satisfies all of the manifold and extremely diverse tasks in equal measure.

However, if there is no central entity operating at a higher level than all the subprocesses in the brain, how is cooperation among the many billions of cells coordinated? How can the brain as a whole form stable activity patterns, how do the distributed processing activities form themselves into the basis for coherent perceptions, and how does such a distributively organized system make decisions? How does this organ know when the various subprocesses have reached a result? How does it assess the reliability of such results? And how does it manage to steer finely coordinated movements?

The initial answer to this bundle of questions is a general one: evolution obviously equipped the brain with self-organization mechanisms that are capable of binding subprocesses and establishing global order states even without a central, coordinating entity. We are, however, still far away from understanding the principles by which distributed processes assemble in the brain to coherent states – states that then serve as the substrates of perceptions, concepts, decisions and actions.

Common mode operation creates cooperation

An experimentally verifiable hypothesis can be elucidated using the example of binding problems that occur when processing visual signals. Due to their specific interconnections, nerve cells in the visual cortex of the brain react selectively to elementary features of visual objects: contours, textures, color contrasts and movements. On higher processing levels are neurons that respond to relatively complex combinations of such elementary features. Initially, this led to the conjecture that the association between elementary features and representations of entire objects was achieved in that cells at the highest level of the processing hierarchy selectively respond to the particular feature constellations of individual objects.

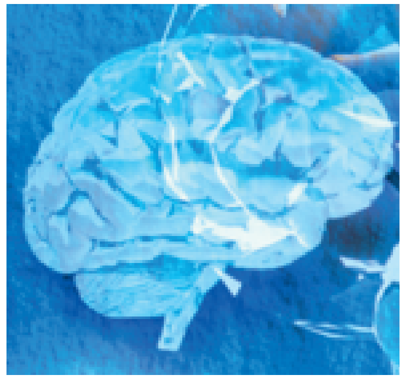
Thus, for every perceivable object, there should be a specialized nerve cell in the visual cortex that then, through its response, signals the existence of this object – but it was never possible to confirm this experimentally. And there is a good reason why nature chooses this option for combining distributed neuronal signals only in exceptional cases, at best – specifically in the case of frequently occurring or very meaningful objects. Otherwise, this strategy would require an astronomical number of highly specialized cells to represent all perceivable objects in all their various forms. In addition, it would be impossible to perceive new objects that we have never seen before, as this would mean that – and this is hardly imaginable – evolution would have had to be provident enough to provide appropriately specialized cells.

Highly developed brains do, in fact, operate according to a complementary, considerably more flexible strategy. They represent objects of perception – whether sensed visually, acoustically or tactilely – through a number of simultaneously active neurons, of which, however, each one encodes just a partial aspect of the whole object.

The cognitive object's neuronal counterpart that can't be reduced any further thus consists in a spatiotemporally structured excitation pattern in the cerebral cortex, produced in each case by numerous cells. Similar to the way in which, through recombination, a limited number of letters yields a nearly infinite collection of words and sentences, the recombination of neurons, each of which encodes individual, elementary features, makes it possible to represent infinitely many objects of perception – even those that we have never seen before. However, this strategy requires that the excitation pattern relay two messages at once: the neurons must report that the special feature they encode is present in the field of view, and they must signal with which other neurons they are currently cooperating.

More than a decade ago, we discovered that neurons in the visual cortex can synchronize their activities with a precision of just a few thousandths of a second, usually generating rhythmic oscillations in a frequency range of around 40 hertz. Then there was the additional important observation that cells, particularly when they are co-involved in encoding a single object, synchronize their activity – they work in common mode, as it were. This led to the conclusion that this precise synchronization of neuronal activities could represent the signature for which cells have temporarily joined to form functionally coherent ensembles. Many laboratories around the world are now focusing on experiments to test this hypothesis.

As is so often the case, here, too, it turned out that the original finding merely uncovered the tip of the iceberg. It is now becoming apparent that neuronal synchronization phenomena are far more functionally significant than first supposed. The latest studies involving patients with schizophrenia reveal one of their implications – possibly the most exciting one: they suggest that the synchronization of neuronal activities in these patients is flawed and imprecise. If synchronization does, in fact, serve to coordinate neuronal operations that take place in parallel and spatially distributed, that would explain some of the dissociative phenomena that characterize this still puzzling disease. The findings could provide new approaches to a targeted search for its pathophysiological mechanisms.



But no matter what solutions we might discover for the diverse coordination problems in our decentrally organized brains, one thing is already clear today: the dynamic states of the many billions of linked and interacting neurons of the cerebral cortex will reveal a degree of complexity that surpasses anything we can imagine.

This doesn't mean that we can't or won't develop analytical methods with which these system states can be identified and tracked in their chronological cycle. But the descriptions of these states will be highly abstract, and they will bear no similarity to our familiar perceptions and concepts that are based on these neuronal states.

To our intuition, it seems foreign that the neuronal correlate of that which we perceive as a solid, tangible object should be a highly abstract, spatially and temporally structured excitation pattern – and that, in this way, not only three-dimensional things, but also smells, feelings or intended actions are represented. And every such representation corresponds to one specific state out of a nearly infinite number of possible states. Or to put it differently, the cerebral cortex system continuously moves from one point to the next in an inconceivably high-dimension space. The trajectory – that is, the trail of this movement – depends on the entirety of all internal and external factors that impact the system.

During its progression through this high-dimensional state-space, the system continually changes because its functional architecture is constantly changed by the experience it gains along the way. Thus, it can never return to one and the same location in this space. This is the reason why we experience time as irreversible. The second time we see a certain object, it effects a different dynamic state than the first time: we recognize it as being the same object, but the new state also encodes the fact that we have seen it before.

These deliberations hint at the abstract descriptions we will have to deal with if we want to gain a deeper understanding of the processes that take place in our brain. This brings us back to the question of why our imagination is so little suited to provide information about the processes that take place in the brain, and thus about its own foundations.

This inability of our imagination is presumably due to our cognitive achievements having adapted, through evolution, to a world in which there was no advantage to concentrating on nonlinear, high-dimensional processes. The dimensions of animals with a nervous system range from millimeters to a few meters – and the cognitive and executive functions of their nervous systems have adjusted accordingly to processes that are characteristic of interactions between objects of this magnitude. And this world is governed by the laws of classical physics that, presumably for that reason, were also discovered before the laws of quantum physics. Classical physics describes the world of solid bodies, causal interactions and non-relativizable coordinates of space and time – the world in which linear models suffice for understanding the majority of all processes that are important to our lives.

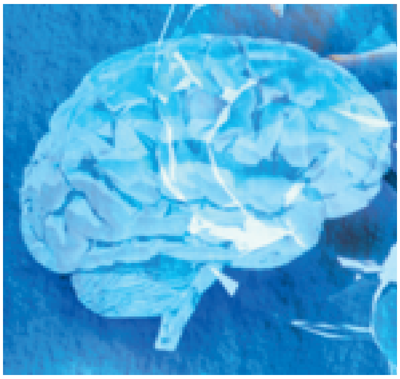
We do indeed observe processes that exhibit different dynamics and appear to contradict our concepts of causality and linearity, but we have difficulty intuitively grasping the laws hidden behind them. The reason we are so inept at imagining nonlinear interactions can probably be explained by the fact that, as living beings, this ability would have been of little advantage to us. After all, organisms benefit from drafting models of processes only when the models facilitate accurate predictions. In highly nonlinear dynamic systems, however, this is generally not possible. Their future development usually can't be predicted, even if all of the starting conditions are known. Thus, there was presumably no selection pressure for the development of cognitive functions that allow us to comprehend nonlinear dynamic processes.

Complexity provides flexibility

This limitation of our cognitive skills could explain why our intuition has developed ideas about the organization of our brain that are at odds with the scientific description of this organ. The human brain undoubtedly constitutes the most complex system in the known universe – and complex does not mean simply complicated. Rather, it is a technical term within the complexity theory and designates specific characteristics of a system made up of many individual active elements that interact in very special ways.

Such systems are characterized by highly nonlinear dynamics; they can produce qualities that can't be derived from the characteristics of the components – and they are creative: they can take on nearly infinitely many states in high-dimensional spaces, creating new, unpredictable patterns. This is because they organize themselves and can take on metastable high-order states without the coordinating influence of a higher-level entity.

But why did nature give brains these properties when they are primarily concerned with analyzing 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 is counting on the particular flexibility and broad range of applications of complex nonlinear systems. After all, they allow for much more elegant solutions to problems in information processing than do linear operations – for example, in recognizing patterns, forming categories, associatively linking large quantities of variables and making decisions.

The ingenious trick appears to consist in transposing the low-dimensional signals our sensory organs provide into high-dimensional state spaces, processing them there and then transforming the results back to the low-dimensional space in which the behavioral reactions occur. It is interesting that we have no insight into the high-dimensional nonlinear processes in our brain, and perceive only the low-dimensional results. That is why we apparently imagine that the same linear processes that we impute to the observable phenomena in the world outside also take place in the brain – and that is presumably also the reason why we believe there must be a central entity at work in our brain.

Intuition invites illusion

Linear systems can't organize themselves. They are not creative. Their dynamics move in unchanging circles, and if a new one is to be created therein, external structuring influences must act upon them – they require 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 brain that coordinates all the various distributed processes and relays impulses for new things. And since 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: the ability to be initiative, to want something, to decide and to invent new things.

This speculation may be a warning to us whenever we interfere in the dynamics of complex systems, whether intentionally or out of necessity. As complex systems, nearly all areas of our lifeworld that comprise numerous active and interacting components exhibit highly nonlinear dynamics – from social and political systems to economic systems and biotopes. By acting, we become active components of these systems, and our action promotes their dynamics and future development. And that confronts us with a grave problem.

Even when it comes to our actions in complex lifeworld systems, we seem to focus primarily on linear models, as we lack the intuition for nonlinear behavior. We thus tend to underestimate the capacity of these systems to self-organize, but at the same time, to overestimate their controllability. Therefore, we consider the most effective strategy for stabilizing and controlling these systems to be establishing central entities that then must regulate the many distributed processes and steer the development of the overall system in the desired direction. A glance at the hierarchical structures in our social and economic systems suffices to recognize that we are only too willing to follow this intuition and put it into action.

But this raises the question of whether we can always trust the abilities of these entities, and whether we don't occasionally overtax them by expecting more of them than they are capable of, even under optimal conditions. For fundamental reasons, the development trajectories of complex systems are open and difficult to forecast, even when the starting conditions are fully known. For the same reasons, it is difficult to foresee how controlling intervention will affect the behavior of such a complex system.

Under these circumstances, it seems prudent to carefully check individual cases to determine how well the institutionalized controlling mechanisms satisfy the dynamics of the respective systems. If the systems are straightforward with primarily linear dynamics, then hierarchically structured, conductor-like controlling structures may be the appropriate option. If, however, the systems are highly complex with strongly nonlinear behavior, then we should set greater store by the self-organizational power and the creativity of such systems – and not prematurely succumb to the illusion that we can selectively intervene. Then it is advisable to structure the mesh of interactions and information flows in such a way that the self-organizing mechanisms can develop optimally.

Nevertheless, we should consider it good news that our lifeworld systems were able to become so developed and still remain tolerably stable. This should encourage us to trust more in the robustness of the structures that have come about through self-organization: no planner, no matter how astute, could have ever designed systems from the ground up that are as complex as our brain or our social and economic structures, and done so in such a way that they would work and remain stable over long periods. ●

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