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The Brain, a Complex Self-organizing System

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Our intuition assumes that there is a centre in our brain in which all relevant information converges and where all decisions are reached. To neurobiologists, the brain presents itself as a highly distributed system in which a very large number of processes occur simultaneously and in parallel without requiring coordination by a central convergence centre. The specific architecture resembles, in many respects, small world networks and raises the question of how the multiple operations occurring in parallel are bound together in order to give rise to coherent perception and action. Based on data obtained with massive parallel recordings, the hypothesis will be forwarded that temporal coherence serves as an important organizing principle and that this coherence is achieved by the synchronization of oscillatory activity in distinct frequency bands.

Introduction

When attempting to summarize current views on the organization of the brain it is appropriate to begin with an epistemic caveat for two reasons. First, there is the problem of self-referentiality because a cognitive system strives to understand its organization using its own cognitive abilities. Second, the brain is one if not the most complex systems known to us and we are aware of the fact that we are far from a comprehensive understanding of its functional organization. From a neurobiological perspective it is obvious that our perceptions and imaginations as well as our abilities to reason are constrained by the cognitive abilities of our brains – and brains, like all other organs, are the product of an evolutionary process. Hence, our brains have become adapted to the conditions of the mesoscopic world in which life has evolved. It is the world within the scale of millimetres to metres, it is the world where the laws of classical physics are more or less applicable, it is not the world of quantum physics or of astrophysics. As a consequence, our cognitive functions have become adjusted to ensure survival in this mesoscopic world. Problem solving in this dangerous and poorly predictable world requires the application of pragmatic heuristics and hence cognitive abilities that are, with all likelihood, not optimized to comprehend the essence behind the perceivable phenomena or the 'absolute truth' in the Kantian sense. Evolution did not prepare us to understand processes at subatomic or cosmic scales, because they were and are completely irrelevant for our daily struggle to survive. Even more worrying is the possibility that the way in which we reason is constrained by adaptation to the narrow range of the world that we can access with our specialized senses. In conclusion, it is very likely that our cognition is constrained and this to an unknown extent. And this may apply not only to primary perception, but also to our way of deriving inferences from observables. If this were true it would pose insurmountable barriers to our attempts to understand as it would also challenge the consistency of mathematical theories and logical deductions. However, for these very reasons we have no way to know where our limits are.

Some current convictions

It is commonly held by neuroscientists that all cognitive and executive functions that we can observe in human beings, including the highest mental activities and consciousness, are the result, not the cause, of neural interactions. Consequently, they follow neural interactions, rather than preceding them. Furthermore, it is assumed that all neural processes follow the known laws of nature. The reason is that we can explain the behaviour of organisms of low complexity, such as for example molluscs or worms, by registering the activity of their neurons and establishing causal relations between the spatio-temporal patterns of this activity and the respective behaviour. We have, at present, no reason to postulate any additional unknown forces, laws or modes of interaction in order to explain their behaviour. Furthermore, all available evidence indicates that neuronal interactions in more evolved brains have only become more complex but continue to obey the same principles. There seems to be no ontological discontinuity in evolution. At present, there is no need to postulate any additional hitherto unknown ingredients in order to explain how our brains function. Of course, we have to take into consideration that we are embedded in a complex sociocultural environment and that the organization of our brains is not only determined by the genes but also shaped by the epigenetic influences of this socio-cultural environment – an aspect that has not been considered enough in the recent past. This is the reason why the fine-grained connectivity of our brains differs from that of our cave-dwelling ancestors despite the rather similar genetic dispositions.

The big questions

One of the fundamental questions concerns the objectivity of perception. Cognitive neuroscience explores from a third-person perspective the mechanisms that mediate our perception and the acquisition of knowledge. The long-standing discussions about the objectivity of cognition – the questions of how constructive our perceptual processes are, how reliable or idiosyncratic – need to be reconsidered on the basis of neurobiological insight. Another hard question, to which the neurosciences will have to find an answer, is related to the mind–body problem: how can mental phenomena, the immaterial entities, such as the qualia of perception, and social realities, such as belief systems, be related to the cognitive and ultimately neuronal functions of individual or socially interacting brains. These immaterial entities are part of our human reality, strongly influence our behaviour and affect our lives. However, they obviously have another ontological status as the cognitive (neuronal) processes that brought these entities into this world by supporting cultural evolution. Yet another burning question is the nature of the neuronal correlates of consciousness and this problem is intimately related to the constitution of the intentional Self and the conundrum of the existence of free will. If neuronal processes are the basis and cause of all mental phenomena and if brain processes follow the laws of nature, then the principle of causality must hold for neuronal interactions. Even though there is noise and interference, each state of the brain is then a necessary consequence of the immediately preceding state. Since decisions are the consequence of special brain states, our concepts concerning the independence of will are likely to require some revision.

The interplay between genetic and epigenetic determinants

Evolution is a conservative process. Once an invention has been made that works, it tends to be conserved unless there is a major change in conditions that makes this invention obsolete or maladapted. This is the reason why our nerve cells function in exactly the same way as those of snails, why the same learning rules are implemented and there are the same mechanisms of signal transduction. In addition, the development of structures followed a very conservative path. Since the first appearance of the cerebral cortex – the six-layered sheet of nerve cells that covers the hemispheres of the brain – no new structures have emerged. There is just more of the same and this increase of hardware makes all the difference. It is the addition of a few more cortical areas that seems to make the difference between the brain of a human being and that of our nearest neighbours, the great apes. Apparently, it is only this addition of processing substrate and the associated gain of complexity that is responsible for the difference between animals and humans, between species that failed and those who succeeded to promote cultural evolution with all its far reaching consequences. In this context, however, one needs to consider that cultural evolution created a socio-cultural environment of ever-increasing complexity that, in turn contributes to the epigenetic shaping of brain architectures. Thus, even if the genetically determined layout of brain architectures has changed only little since the beginning of human civilizations, those features that can be modified by epigenetic shaping are likely to have undergone major modifications. However, these modifications affect mainly the dense meshwork of local intracortical connections rather than the general layout of brain structures and their interconnections.

The distributed organization of the brain and wrong intuitions

A major challenge to both brain research and our intuitions is the distributed organization of our brains. The neurobiological evidence accumulated over the last decades has led to radical changes in our views of the brain. In the early days, intuition and introspection were the major sources of knowledge for the formulation of hypotheses about the organization of the brain. Now we learn that these intuitions are in drastic conflict with the evidence provided by scientific investigations, raising the interesting question of why the brain is so agnostic to its own organization. We do not feel our brain, have little intuitive insight into its processes and are surprised to find that it is organized according to principles that differ substantially from what we have been assuming. Intuition suggests to us that somewhere in the brain there ought to be a convergence centre where all information is coming together to be amenable to coherent interpretations of the world. This would be the site where perception takes place, where the intentional agent is active, where decisions are reached, where plans are developed and where the Self is seated. We assume hierarchical structures and we also recreate them in the social and economical world – probably not always to our advantage, because they may be maladapted when systems become very complex.

The reality of our brains is very different. The cerebral cortex comprises a large number of different areas that, depending on their input, accomplish different functions but use similar computational algorithms. Thus, the format of exchangeable information is always the same and communication among cortical areas can capitalize on this *lingua franca*. This is a necessary prerequisite for generalization, abstraction, symbolic encoding and, last but not least, for the constitution of the unity of consciousness. The surprising finding is that the connections linking these areas provide only little evidence for serial processing in strictly hierarchical architectures. Rather, the connectivity scheme is dominated by principles of parallelity, reciprocity and distributedness. Thus, neurons located in the visual cortex can talk directly to neurons in the limbic system or in executive areas, and most of these interactions are reciprocal. This meshwork of connections is extraordinarily dense and complex but far from random. It is highly structured and has properties of so-called 'small world networks'. This architecture is the hardware realization of the programs according to which brains process information and it is also the basis of stored knowledge.

Distributed representations

Imagine one perceives a barking dog, touches its fur and judges the dog as friendly. In this case all visual areas will be active and participate in the identification of the dog, the same holds for the tactile areas, which analyze the texture of its fur, the auditory areas that decode the barking and the limbic areas that add the emotional connotations. There is no single locus for the representation of the integrated percept of this dog. Rather, the representation consists of a complex spatio-temporal pattern of distributed neural activity. Thus, the brain presents itself as a highly distributed, self-organizing system. It lacks the postulated singular convergence centre, which Descartes actually searched for in cow brains and thought he had found in the pineal organ, because it is 'impair' in contrast to pairwise, occurring only once like the hypophysis. In reality, however, there is no such centre, no observer, no coordinator; there is no identifiable seat of the conscious, intentional self. The brain is a distributed system that self organizes and produces all those extraordinary phenomena that we as observers attribute to the person, the Self. The question then arises: why is our intuition so wrong? My suspicion is that the brain, even though it exhibits nonlinear dynamics, is tuned to assume that the processes to be analyzed are linear in order to be able to make reasonable predictions. However, if the brain assumes the same concerning its own functioning, if it assumes that it executes mainly linear operations, it is bound to postulate a mover, because linear systems cannot by themselves produce all the remarkable functions that we observe, they cannot be creative, open towards the future and intentional.

The binding problem

Self-organizing, distributed and goal-directed systems need efficient and flexible mechanism in order to coordinate and bind, in a context-dependent way, the many distributed local processes into coherent wholes. One way to bind distributed results is convergence in devoted anatomical circuits. If the messages encoded by units A and B are to be bound it suffices to connect their outputs with a third unit C and then to select appropriate thresholds for unit C, so that C is only active when A and B are active at the same time. In this way relations can be evaluated in rigid, anatomical architectures and expressed by the responses of conjunction specific neurons. The brain uses this strategy, but because of its rigidity and inflexibility, this strategy can applied only for the encoding of frequently occurring stereotyped relations. The alternative is to express relations by dynamic signatures, so that the representation remains distributed but functions as a coherent whole, a strategy called assembly coding. It is a much more flexible coding strategy, because it shares features with language systems. With 26 letters one can write the world's literature, simply by re-combining in a flexible way the letters. With 10^{11} neurons, each having the role of a symbol, and a flexible recombination mechanism, a virtually infinite number of different distributed representations can be formed. The representations of novel objects, of the ever changing constellations of real world conditions and of adaptive motor responses, are, thus, implemented best by dynamically configurated assemblies. However, in assembly coding, one needs a code that defines from instance to instance which subset of the myriad active neurons actually contributes to a particular representation. As there will always be several coexisting assemblies, an unambiguous signal is needed that tells to the rest of the brain which neurons are actually bound together in an assembly. Therefore, neurons supporting assembly codes have to convey two messages in parallel. First, they have to signal whether the feature for which they serve as symbol is present and, second, they have to indicate, in parallel, with which other neurons they are actually collaborating in order to form the coherent whole to which they contribute their feature. There is common agreement that they signal the presence of the feature for which they stand as symbol, by increasing the frequency of their discharges, by becoming more active. Following a discovery made in our lab in Frankfurt we pursue the hypothesis, that the signature for the *relatedness* of the cells belonging to an assembly is the precise synchronization of individual discharges that, in most cases, undergo in addition an oscillatory modulation. The required precision is in the range of milliseconds which, in principle, allows the definition of relations with the temporal resolution necessary to reconfigurate assemblies at a rapid pace. I shall not discuss the technical details that suggest that synchronization is an excellent tag for the definition of relations. Intuitively, it appears as obvious that events that happen simultaneously are easily bound together. And there are indeed mechanisms that render neurons particularly susceptible to synchronous, i.e. coincident inputs.

Since the discovery of stimulus dependent synchronization of oscillatory responses, many laboratories have joined the search for its functional implications. A major prerequisite for those studies is to sample simultaneously the responses of at least two neurons, preferably of as many as possible, because otherwise temporal relations cannot be assessed. In this context it is noteworthy that, until recently, we used to record from only one neuron at a time and related the firing of these isolated cells to stimuli or behaviour in order to identify their functional properties. This precluded analysis of relations and hence the identification of functionally bound assemblies. If one considers the complexity of the system it is obvious that even the multisite recordings have their limits. We are, despite all progress, still at the very beginning of understanding the brain processes underlying higher cognitive functions but we seem to know how to proceed. We have decades ahead of us, where we shall need more and more theoretical approaches and new technology, but we know where to go. Since its discovery, synchronization of oscillatory activity has become a candidate mechanism for many different functions. One is the already mentioned dynamic binding, the flexible definition of relations. However, synchronization also seems involved in attentional mechanisms that select signals for further processing. It appears to serve the readout of information that is stored in the connectivity and it also appears to be used to bind different sub-systems together such as sensory and motor systems. Evidence also indicates that synchronization of oscillatory activity serves the selective routing of signals across the highly interconnected networks of the cerebral cortex. The mechanism resembles the tuning of a radio to the frequency of a certain transmitter, thereby allowing brain centres to send a message with high selectivity from point A to point B without spreading it to the numerous other, also connected, structures. This selective routing is a very difficult problem in a highly connected system and may be solved by synchronization of oscillatory activity. There are also indications that entrainment into coherent oscillations plays a role in the storage and maintenance of information in short-term memory; and, finally, large-scale synchronization appears to be a prerequisite for signals to have access to conscious processing.

An outlook

The more we learn about the brain the more abstract will the descriptions become because we shall be dealing with increasingly complex assemblies of neurons and the spatio-temporal patterns generated by these assemblies. These patterns are with all likelihood non-stationary and best described as dynamic trajectories of a highly nonlinear system. Probably, these trajectories never repeat identically because, if they did we would have no notion of time. Many of the explanations that we will come up with, and this has already started, will further be in conflict with our primary intuitions. We have no feeling for the processes in our brain and, in addition, we have difficulty intuitively understanding the properties of complex nonlinear systems. In principle, one can identify the dynamic patterns generated by neuronal assemblies by registering the activity of many neurons simultaneously and using advanced mathematical methods in order to describe those patterns. This approach will result in abstract descriptions that are not tangible and difficult to represent in two or three dimensions. They will consist of lists of numbers or systems of equations that are remote from our intuitions about the neuronal correlates of a percept, a thought or a feeling. Furthermore, we will have to consider more and more that the brain is a member of a socio-cultural network and that some of the phenomena that seem to be so difficult to explain in pure neuronal terms will have their explanation only when considering interactions among brains, or networks of brains. This widened perspective is probably necessary to close the explanatory gaps between first and third person perspective. We shall have to consider the fact that our brains are the product of their embedding in a complex cultural environment and that many of the constructs that are so difficult to relate to brain processes, such as value systems, consciousness, intentionality and so forth, have only come into the world because brains mirror themselves reciprocally in other brains and assign properties to the then gained experiences. We are just at the beginning of social brain research but there are already first investigations on phenomena that exist only in the realm of social interactions, such as empathy, greediness and jealousy. Obviously, the complexity of these networks formed by interacting brains by far exceeds the complexity of individual brains.

Further Reading

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About the Author

Professor Dr. Dr. h.c. mult. Wolf Singer studied Medicine, in Munich and Paris, obtained his MD from the Ludwig Maximilian University in Munich, and his PhD from the Technical University in Munich. Since 1981 he has been Director at the Max Planck Institute for Brain Research, Frankfurt am Main. In 2004 he was the founding director of the Frankfurt Institute for Advanced Studies (FIAS) and in July 2008 he initiated the foundation of the Ernst Strüngmann Institute (ESI) for cognitive neurosciences. His research is focused on the neuronal substrate of higher cognitive functions, and especially on the 'binding problem'. How these distributed sub-processes are coordinated and bound together in order to give rise to coherent percepts and eventually conscious awareness is a central question of current research. His work was honoured with many scientific prices and two Drs. honoris causa.