OCTOPUS EMBODIMENT AND COGNITIVE BRAIN FUNCTION

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Being a Fellow of the Wissenschaftskolleg was a very special, interesting, and unusual experience for me, detaching me from the highly interactive way of life in laboratory and classroom for ten months. I feel that this period has brought important additional intellectual insights to my scientific goals. In this report I would like to sketch some of the ideas emerging from my stay. I should warn the reader that many of these ideas are preliminary and some are based on a first approach to areas beyond my immediate field of knowledge and profession.

I was trained as neurophysiologist at the Hebrew University and in the laboratory of Eric Kandel at Columbia University. At that time (late ’70s and ’80s) neurophysiology was still a developing field. My fellow students and I had the privilege of following several leading figures like Sir Bernard Katz, Steven Kuffler, Eric Kandel, John Nicholls, Josef Dudel, Itzchak Parnas, and Rami Rahamimof, who advocated the bottom-up approach, i.e., using simple preparations for researching basic neuronal mechanisms. The rationale was that this approach could reveal universal properties of the nervous system that would then help us understand how complex nervous systems function.

Since then the situation has changed. We have now accumulated such a huge amount of information on the various processes in nerve cells that I doubt whether this bottom-up approach is practically feasible. And, despite this abundance of details, we still know little about how a brain achieves complex cognitive functions.

Over the years I found myself becoming more and more interested in how simple cellular processes may be involved in complex neural functions. Analyzing simple motor systems may help explain how animals efficiently control multiple degrees of freedom, as well as aiding the design of better robots. Moreover, such analysis may even suggest possible intelligent properties that may emerge from this simple organization. We followed this approach in my focus group in the Wiko (Functional and Structural Constraints in the Evolution of Sensorimotor Networks) that concentrated on a "simple system". However, I still feel that different approaches are needed to advance our understanding of how complex brains carry out cognitive functions.

Cognitive functions are usually thought to include processes such as learning and memory, association, language, problem solving, decision making, mental imagery, and more. I have developed a mechanistic approach that may help conceptualize these terms within a neurophysiological framework. I view cognitive processes as emerging through integrative processing of sensory and motor information with stored memory representations. In this mechanistic scenario, in contrast to the prevailing dogma, memory itself is not considered a cognitive function. It is worth noting both that certain animals without obvious high cognitive abilities show excellent memories and that humans with cognitive disorders may still possess an excellent memory.

Over the last fifteen years, my collaborators and I have studied the nervous system of the octopus (*Octopus vulgaris,* class Cephalopoda, phylum Mollusca). Based on its behavior, the octopus is considered the most advanced invertebrate. Its nervous system has the largest number of nerve cells of any invertebrate – around 500 million neurons, similar to the nervous system of a dog. I am fascinated by two special features of the octopus, its highly maneuverable eight flexible arms and its highly advanced and complex behavioral repertoire. These are, I believe, especially suitable models for furthering my scientific aim of better understanding how the brain is involved in complex behaviors.

During my sabbatical year at the Wiko, the Colloquia given by other Fellows, the informal discussions, and the ideas raised in my Focus Group have all served to strengthen my belief that octopuses and other cephalopods are ideal animals for researching complex brain functions, including those vaguely defined as cognitive. One reason for the strengthening of this belief was my becoming more familiar with the term "cognitive embodiment". Although the concept is a little vague, its main point lies in viewing the behavioral complexity of robots, animals or human beings with reference to their being embodied entities. That is, complex behaviors of an agent (animal or human), including cognitive functions, stem from the highly dynamic interactions between the agent and the environment through the physical interaction of the body with the environment and the resulting sensory and motor information. In this view the controller (i.e., the nervous system) is an integral component but yet only one part of this embodied whole. This is well explained by Pfeifer et al. (2007): "Clearly, the embodied view suggests that the actual behavior emerges from the interaction dynamics of agent and through a continuous and dynamic interplay of physical and information processes."

This view is also interesting because it implies "self-organization" in the establishment of embodiment. Self-organization is a very attractive idea for explaining the highly adaptive properties of especially complex nervous systems. Indeed, self-organization may be a biological characteristic of "complex brains". Some dramatic differences that we find in the organization of a learning and memory area in octopus and cuttlefish brains may suggest that self-organization is a basic neural property from which high adaptability arises.

If this embodied view is correct, then it becomes very clear that the controller (the brain in the case of animal behavior) must be the most adaptive component. Thus, it is no surprise that all nervous systems are endowed with short- and long-term plasticity, which we usually implicate in learning and memory. There is every reason to assume that such plasticity processes are directly involved in the self-organizational processes. This idea is supported by the recent discovery of how relatively easy it is to "train brains" to generate a meaningful output (e. g. in brain-machine interface).

Within the framework of "embodied intelligence", embodied agents are seen as being comprised of four dynamically interconnected elements: the controller, the mechanical and the sensory system, and the environment (Pfeifer et al., 2007). It is clear, however, that some animals have relatively simple embodiment, while in others it is very complex, that is, all four parts are complex. The octopus is one example of a very complex embodiment with its amazingly large sensory system comprising hundreds of millions of sensory cells (visual, tactile, chemical) and large eyes, and its two highly complex motor systems (one for the highly maneuverable arms and soft body and one for the complex image-generating chromatophore system). In addition, the very large nervous system with 500 million neurons provides the substrate for an appropriately complex controller that must be dynamically integrated into the embodiment. Yet, in spite of the complex embodiment and large central nervous system, the octopus brain is rather simply organized. In other words, this somewhat philosophical concept of "embodied intelligence" has helped me perceive cephalopods as a special group of invertebrates, whose relatively simply organized nervous system makes them extremely useful for unraveling concepts and principles underlying complex behaviors.

Continuing this line of thought, I argue that we have a better chance of understanding complex nervous systems by examining those that have evolved from simpler elements with a simpler connectivity. Our electrophysiological studies have shown that the biophysical properties of the neurons in the octopus brain still maintain typical simpler invertebrate characteristics. That is, the cephalopods present the most complex brains that are still constructed from simpler nerve cells. In addition, cephalopod brains are also more simply organized, more like typical invertebrate ganglia than the multi-layered highly interconnected vertebrate brain tissue.

It has been proposed that the main difference between vertebrate and invertebrate nervous systems lies in the level of complexity of the nerve cells (Emes et al. 2008). If this is so, then I believe that, appropriate to their simpler cellular mechanisms, the cephalopod neural networks must also be more simply organized than vertebrate networks. The vertebrate networks can achieve great complexity with a smaller number of neurons due to their more versatile properties. In contrast, invertebrates, with their simpler neurons, would need to develop larger networks, but with simpler connectivity, to achieve a similar level of complexity. Possible support for this suggestion comes from comparing the number of cells in the vertical lobe of the octopus and the vertebrate hippocampus, brain structures important for learning and memory. The octopus vertical lobe contains about 25 million neurons, only half the number of neurons in the human hippocampus (about 50 million) and almost seven times more than in the rat hippocampus (about 3.6 million neurons). I believe such a basic difference in complexity of organization makes the cephalopod brain much easier to explore.

I am grateful to the Wissenschaftskolleg for providing me with the opportunity to enrich my perspectives in relating behavioral complexity to brain mechanisms and organization. I have returned to Jerusalem with greatly strengthened enthusiasm to continue my research on octopus and other cephalopods. Not only do I aim to contribute to the better understanding of complex brain functions, I hope also to succeed in persuading more neuroscientists of the advantages of researching cephalopods.

References

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