Session II: The Neural Mind

NEUROSCIENCE, BRAINS, AND COMPUTERS

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SUMMARY: This paper addresses the role of the neurosciences in establishing what the brain is and how states of the brain relate to states of the mind. The brain is viewed as a computational device performing operations on symbols. However, the brain is a special purpose computational device designed by evolution and development for survival and reproduction, in close interaction with the environment. The hardware of the brain (its structure) is very different from that of man-made computers. The computational style of the brain is also very different from traditional computers: the computational algorithms, instead of being sets of external instructions, are embedded in brain structure. Concerning the relationships between brain and mind a number of questions lie ahead. One of them is why and how, only the human brain grasped the notion of God, probably only at the evolutionary stage attained by *Homo sapiens.*

1. The neurosciences and the self-image of Man

Probably no other science to-day is as important as the neurosciences [1] in constructing our image of Man. That is because understanding the brain directly addresses the questions of the physical substrates and mechanisms underlying perceptions, memories, feelings, beliefs, values, decisions, actions etc. Several of these questions have been the target of philosophical quests, often of religious choices, sometimes of evolutionary or historical interpretations. Now they seem to be answerable by rigorous scientific investigation.

The central project of the neurosciences assumes that states of the mind can be mapped on states of the brain. Indeed, the modern tools of functional brain imaging have gone a long way to suggest that this is feasible. Nevertheless, the project will be proven to be really possible only when, by reverse computation, we will be able to identify the states of the mind from «reading» the states of the brain. And we are not there yet. Difficulties lay in the absence of methodologies which could monitor brain states in real time, with very high spatial (cellular) and temporal (in the ms range) resolutions. Even more fundamental difficulties

[1] The term «neurosciences» requires specification. It refers to the convergence of studies of brain structure (neuroanatomy and neurohistology) of brain function (neurophysiology) and molecular investigations of the brain (neurogenetics, neurochemistry, neuropharmacology) with animal or human behavior (neuropsychology, cognitive psychology) into an integrated field. In this field, different levels of organization, from molecules to mind in animal or human models are crossed in order to understand the brain in all its expressions. The neurosciences are not to be confused with neurology or psychiatry which deal with pathological conditions, the explanation of which ultimately lies within the advances in understanding the brain through the neurosciences.

lurk in the possibility that states of the mind and states of the brain do not map onto each other one-to-one, but that one state of the mind might correspond to several states of the brain. Furthermore, there might be individual differences in the relation between brain states and states of the mind. Nevertheless, neuroscientists are well aware that the perspective of mind reading raises obvious ethical questions, to be dealt with by society.

2. The brain in development and evolution

It seems unavoidable to accept that our grasp of reality, were it physical or metaphysical has its origins in the brain. Of course reality exists outside the brain as one cannot escape noticing when a mistake in the appreciation of that reality comes at a cost. But our grasp of reality is the result of the interaction between our brains, including our sense organs and the world. And our reality is not the same as that of animals which, for example, can perceive ultrasounds or polarized light. It is also not the same as that of animals which can freely move in a three dimensional space, were it water or air. Nevertheless the co-evolution of the animal kingdom has achieved a high degree of consensus between different species in the appreciation of outside reality. The consensus is so high that humans are prone to extending to animals attributes of their own mind.

Two processes occurring at very different time scales, millions of years vs. days but using very similar mechanisms are responsible for constructing the brain and, indirectly, for the special grasp of reality that our brain achieves. These processes are evolution and development. They are closely interrelated not because development recapitulates evolution, but because evolution proceeds by modifications of development. Thus, it may not surprisingly that evolution and development use similar mechanisms, to achieve the diversity that we know in the «biosphere», as I have elaborated elsewhere (Innocenti, 2011).

3. The computing brain

The question I wish to briefly address here is whether evolution and development, in creating the animal brain, have manufactured a computational device. This is somewhat of a crucial question because the answer might place our self-image at the level of mechanical determinacy and predictability of a computer or of a lawn mower.

When in the eighties David Marr (1982) and then the PDP research group (1986) forcefully advocated the notion that neural operations are computational in nature, I was taken off-guard. The issue lied much with the very notion of computation, which came to encompass any transformation of symbols according to specified rules. Turing machines were viewed as the computational devices «par excellence» and the brain became to look as a Turing machine.

It is hard to deny that, according to the above definition the brain performs computational operations. Henry Markram and colleagues added a twist to the computational style of the brain by proposing that the brain performs liquid computations, rather as the size, location and velocity of a fallen stone can be computed from the ripples it generates in a basin of still water (Maass *et al.,* 2002).

But does it follow that the brain is a computer? What I write below has no pretention of answering the question. But one cannot ignore some profound differences between the brain and the man-made computational devices as we know them to-day.

3.1. *The brain consists of incredibly large numbers of non-identical elements*

Neurons come in a broad variety of sizes, shapes, firing properties and genetic make-up. The classificatory efforts of 19th century neuroanatomists, in particular Ramon y Cajal have identified classes of neurons which share certain morphological features, e.g., shape of their soma and dendrites and/or distribution of their axons. Some of these classes, for example the non-pyramidal neurons of the neoocortex, include elements which differ profoundly in almost all their properties (Markram *et al.,* 2004). Other classes, in particular the pyramidal cells of the cerebral cortex, probably the commonest cell type in the brain, consist of an apparently more homogeneous set of neurons which share morphological and molecular properties and yet are always somewhat different from each other. In particular, the diversity of their axonal calibers, the part of the neurons which establishes contact with other neurons has interesting consequences for neural processing (Caminiti *et al.,* 2009; Innocenti, 2011).

3.2. *Each element of the brain is a computational device*

Indeed, each neuron performs algorithmic transformations of the inputs it receives. Both the somato-dendritic part of the neuron and its axon (Innocenti, 2011) perform computations, not necessarily related to each other. The computational algorithms are determined by the physical-molecular structure of the neuron mainly the diameter and length of the dendritic and axonal branches, the distribution of membrane receptors and ionic channels, not by external instructions. Since neurons differ from each other, they also perform different computations. If we take the example of cerebral cortex with an estimated 2.600 million neurons (Pakkenberg, 1966) or more we are clearly dealing with a network of computational devices beyond imagination. And at least as many neurons do exist in the rest of the brain. Although each neuron is a computing element in its own right, most neural operations are collective computations, performed by neuronal assemblies. In this respect brain function has a «holistic» flavor. It is usually believed that the computing assemblies are flexible, in the sense that they are task-dependent, ephemeral, since they are continuously created and dissolved, and a neuron can take part in different assemblies.

3.3. *Memory elements are embedded in each computational operations*

This is due to the fact that the strength of the connections between two neurons changes over time, depending on the past history of the connections. Interestingly this phenomenon now called synaptic potentiation (or depression) was anticipated by Freud (1895), as noticed also by Centonze *et al.* (2004).

3.4. *The brain is a slow processor*

This seems to be paradoxical in view of the fact that brains perform effortlessly operations that the fastest computers cannot match (below). In the course of evolution the brain enlarged progressively, from the about 400 cc of *Australopithecus* to the current, roughly 1500 cc. Because the diameter, and hence conduction velocity of cortical axons did not keep up with this volumetric enlargement, the brain became a progressively slower processing device (Caminiti *et al.,* 2009). One possibility is that the brain takes advantage of the slow processing, perhaps because this allows expanding the time span of processing «windows», hence enriching cortical dynamics (Caminiti *et al.,* 2009; Innocenti, 2011).

3.5. *The brain is self-organizing*

That is, the hardware of the brain, neurons, non-neuronal elements, blood vessels etc. attain their structure, position and reciprocal relations, interconnections in the case of neurons, over a more or less protracted (depending on species) developmental period, in the absence of an external craftsman.

3.6. *The brain can, to some extent, self-repair*

Much, perhaps too much, is made in current clinical publications of the self-repairing properties of the brain, which usually comes to be labeled as «neural plasticity». Nevertheless, we had the opportunity of studying in a few patients a remarkable functional recovery, in spite of profound alterations of cortical structure (Kiper *et al.,* 2002; Zesiger *et al.,* 2002).The mechanisms underlying self-repair are usually not known, although there are some candidates.

3.7. *The brain generates the sense of self and concepts of ethics, beauty, purpose*

As we all know, and sometimes it can be a problem.

3.8. *The brain is capable of free decisions, at least sometimes*

This has, surprisingly, become a controversial issue, which would, in itself, justify a full chapter or a scientific meeting in the Sofia-Iberia format. The conclusions on the existence and nature of free will have obvious consequences for ethics and law. I cannot ignore my personal belief, based on subjective experience, that my choices are indeed free, although often prepared by some subconscious brain processes. And sometimes they have to run against some severe external or internal constraints.

3.9. *The brain was tinkered by evolution for special-purpose computation*

The brain not unlike wings, teeth, claws etc. evolved differently in different species, as a physical tool, aimed at improving individual survival and reproduction in a given ecological niche. In development, brain structure and function need validation by specific interactions with the environment. When these are missing, parts of the brain and the functions they perform atrophy. This is most clearly observed in situations in which animals (and occasionally humans) are deprived of the critical interactions with the environment in early stages of brain development (reviewed in Innocenti, 2007).

The fact that the brain was tinkered in evolution as a special purpose computational device probably underlies the main differences between brains and computers of the Turing type. Among these differences a crucial one is that the software of the brain, i.e. its computational algorithms, is intrinsic to the design of its constitutive elements, it is not written as a set of instructions which modify the state of the brain. What comes from the environment is the input that the brain processes, coded in neuronal activity.

4. Conclusions and perspectives

None of the properties listed above applies to computers and this emphasizes the huge differences between brains and man-made computational devices. These differences do not invalidate the notion that the brain might be viewed as a computational device. Rather, they redefine the concept of what a computational device can be, although presumably out of reach of current human technology. And still we have scratched only the surface of what the brains is. Some frontiers lie ahead. They include the technological advances needed to monitor large neuronal assemblies in a multidimensional state space, including, at least, firing frequencies, phase relations, directional connectivity, topological relationships of the assembled neurons. Until the appropriate methodologies will be developed the state of the brain will remain undetermined, although in ways rather different from Heisenberg's indeterminacy. Frontiers include the need of understanding volume transmission, i.e. the communication between neurons, as well as between neurons and non neuronal elements via the extracellular compartments, in addition to via axons (Agnati *et al.,* 2010). They also include the possibility of incorporating quantum influences on brain function, for example in the emergence of consciousness (Hameroff, this volume). Unfortunately consciousness is usually an ill-defined and overhemphasized notion (what about the wisdom and freedom of subconscious brain processing, the largest fraction of our brain processes?).

Also, the possibility that quantum mechanisms may affect brain function is usually received with skepticism both by physicists and neuroscientists (Koch and Hepp, 2006; Smith *et al.,* 2009; McKemmish *et al.,* 2009, and references therein). Skepticism does not imply rejection, but it seems that experiments on the role of quantum phenomena in brain functions will be extremely difficult to perform. And in any case the results will not be interpretable outside the large amount of data and concepts that the neurosciences have accumulated over the last couple of centuries. A neural system in which quanta seem relevant to brain function is the visual system, where retinal photoreceptors can be activated by single photons. In this case, though, the impact of quantal light-stimuli is amplified by a complex chain of macro-molecular events (e.g. Nicolic *et al.,* 2010) which seems to override and obscure the physical properties of the stimulating quanta.

As one of the colleagues in the audience uttered (perhaps rephrasing Christof Koch): «trying to explain consciousness (I add: the soul, or even God) on the basis of quantum physics amounts to trying to explain one mystery (or several) with another mystery». Have we lost Occam's razor? For the time being the dialogue between neuroscience and religion shall probably be more fruitfully articulated by asking why and how, in evolution, only the human brain has grasped the notion of God and probably only with the appearance of *Homo sapiens'* brain. Also, the dialogue between science and religion that «Pensamiento» so effectively fosters [2], would be most profitable if religion could develop some sharp operational tools to separate true from false, as science as done.

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