Biochemical and Biophysical Research Communications 564 (2021) 1–3

Contents lists available at ScienceDirect

Biochemical and Biophysical Research Communications

journal homepage: www.elsevier.com/locate/ybbrc

Rethinking cognition: From animal to minimal

In its current use, cognition refers to all activities and processes dealing with the acquisition, storage, retrieval, and processing of information, and this seems to imply the involvement of a relatively complex nervous system. The term "relatively complex" usually refers to a direct comparison with the human or primate brain. And most research on comparative cognition and its neural bases has been restricted to a limited range of species within the vertebrate taxonomic groups. In the last 20 years, however, comparative research has been accumulating a huge bulk of scientific evidence for a wide range of processes in a variety of distantly related species, that seem to imply cognitive phenomena. Intriguing evidence of sophisticated behaviour has come from models which are extremely distant from primates, sometimes organisms with miniature brains. Great attention has attracted the (unexpected by many) evidence of cognitive behaviour in invertebrates and even in organisms classified outside of the Animal Kingdom. In 1980s Humberto Maturana suggested that: "*Living systems are cognitive systems, and living as a process is a process of cognition*", extending this statement to all organisms "*with or without a nervous system*" [1]. This was of course anticipated by the famous statement by Konrad Lorenz according to whom "*Life itself is a process of acquiring knowledge*" [2].

The present collection of articles originates from the idea that time has come to take a more thorough and comprehensive view of the overall evidence of cognition available, devoid of any anthropo- or primate-centric assumption. This special issue aims at offering a bird's-eye view on a selection of key studies focusing on model organisms as diverse as possible, with the aim of unveiling to the readers a more comprehensive meaning of cognition. As a second goal, we would like to facilitate an interdisciplinary dialogue crucial to (re)discuss a common glossary, and even a shared theoretical frame for the existing evidence.

Convincing evidence of intelligent behaviour in (only literally) pin-brained organisms has recently come from Invertebrates, the most widely studied species possibly being the honeybee. **Srinivasan** [3] highlights how foraging honeybees readily collaborate in experimental designs and offer an ideal model for the investigation of a wide range of perceptual and cognitive processes, particularly those related to navigation. The understanding of visual guidance during bees' flight has then been exploited in algorithms for guiding aerial vehicles. Besides Insects, Arachnids are the other Arthropoda Class providing extremely insightful models. **Cross and Jackson** [4] contribute novel evidence of flexible decision making in a member of the Family Salticidae. These jumping spiders plan ahead the walk which leads to a preferred prey (chosen with respect to a path leading to a less preferred prey) on the basis of the integration of visual and olfactory cues. Within Invertebrates, the list of ideal model organisms seems to have only just started. **Schnell and Clayton** [5] stress the importance of extending the comparative approach to a wider range of Invertebrate Classes. In particular among Mollusks, Cephalopods seem to offer an insightful model of independent evolution: their very large and peculiarly organized (distributed) brain as well as their complex behaviour can be directly compared with those of large-brained vertebrates, leading to a more comprehensive grasping of the principles governing cognitive evolution. The understanding of specific aspects of cognition, not long ago considered inviolable domain of humans, have already been broadened by incorporating evidence from non-vertebrates. For example, **Bortot, Regolin and Vallortigara** [6] review the main studies on numerical abilities of invertebrates, discussing the hypothesis of a general mechanism for processing of discrete (i.e., number) as well as continuous (e.g., space) dimensions. On the other hand, concepts and paradigms originally employed in humans could successfully apply also to invertebrate species. **Winsor, Pagoti, Daye, Cheries, Cave and Jakob** [7] extend to invertebrates methodologies traditionally used to study visual attention in humans and other vertebrate species. The authors illustrate how introducing a precise measure of gaze direction in invertebrates could sharpen our understanding of perceptual and cognitive processes.

It appears now clear that intelligence is not confined within a single Taxa, neither can it be confined to a single Kingdom. In this phase some scaffolding seems needed to prompt a shared vocabulary and a constructive dialogue between scientists with distinct backgrounds. **Calvo and Trewavas** [8] dedicate their article to inform scientists focusing on animal organisms about the function and the mechanisms at the basis of plant intelligence and cognition.

It may for example seem unexpected how movement is a pervasive quality of plant behaviour, and that movement in plants is supported by quite sophisticated mechanisms. **Ceccarini, Guerra, Peressotti, Peressotti, Bulgheroni, Baccinelli, Bonato and Castiello** [9] show that while climbing towards a goal, plants can plan and even strategically adjust their movements through the use of sub-movements, as the authors demonstrate using three-dimensional kinematic analysis.

Straightforward stimulus-evoked responses should neither be taken for granted in brained organisms. **Brembs** [10] brings to attention key evidence from animal studies which falsify the "sensorimotor hypothesis", the hypothesis that neural substrates passively react to external stimuli. The author highlights how nervous systems dynamically change their connectivity and can actively generate behaviour.

Complementing this perspective **Wystrach** [11] uses the case of insect navigation to discuss how decision making may well precede neural processing. Rather than being a consequence of a central brain, behaviour seems to emerge from the distributed interactions

https://doi.org/10.1016/j.bbrc.2021.05.055

among various computational centres, body included.

It is important to stress that cognition refers to the processes of acquisition, storage, retrieval and processing of information *irrespective* of whether these processes are conscious. In this regard, some of the authors of the Special Issue seem to be inclined to argue that even single cells are capable of at least some of these processes. **Dussutour** [12] reviews evidence that single cell organisms (slime molds and ciliates) display habituation, the simplest form of learning, and move to discuss evidence suggesting that single cell organisms might undergo even more complex forms of learning such as associative learning. **Gold and Glanzman** [13] discuss this issue with respect to the role of synaptic plasticity in learning and memory, which is a very hot topic in neuroscience nowadays but also a recurring old theme (see e.g. the studies of the 50s′ and the 60s' on Pavlovian conditioning in the ciliate *Paramecium Aurelia* and in the planarian, see for a recent reconsideration [14]). Gold and Glanzman [13] argue for nuclear, rather than synaptic, mechanisms for long-term memory storage.

Levin [15] moves beyond minimal cognition in single cells arguing that the integration of many active subunits into coherent units at a larger scale of organization is a key to evolutionary cognitive science. He stressed that the canonical approach to the study of evolved animal bodies (either single or multiple cells) should be complemented by the study of the plasticity of dynamic morphogenesis of biological forms as revealed by regenerative biology and controlled chimerism. In particular, the development of functional biobots, synthetic living machines with behavioral capacity, could provide new methods for understanding the origin of cognition in all of possible forms of material implementations.

Shapiro [16] maintains the claim that all living cells are cognitive. He discusses evidence that even prokaryote cells display sophisticated regulatory networks establishing appropriate adaptations to environmental conditions and also display capabilities for intercellular signalling and multicellular coordination.

However, the issue of the possible existence of sentience, i.e. conscious experience, in non-human animals and, in particular, in those organisms that have miniature brains, or in plants, or even at the level of single cell organisms is a quite hot and controversial topic. This is reflected by the variety of positions put forwards in this dedicated issue.

Reber and Baluska [17] argue that sentience and life are coterminous, and that consciousness thus emerged 3.5 billion years ago with the first forms of life. They argue for a Cellular Basis of Consciousness (CBC) model according to which sentience would emerge on the basis of inherent cellular activities via processes that take place in excitable membranes of their cells. The theory of CBC would imply of course that plants are sentient as well. The argument is supported by **Calvo, Baluska and Trewavas** [18] that search for foundation of consciousness in plants in the Integrated Information Theory (IIT) of Giulio Tononi [19]. According to Calvo et al. [18] IIT indicates that consciousness can be located on a scale: the maximum being represented by the human brain, the minimum, by a single cell. This conclusion would be in agreement with that advocated by Reber and Baluska [17] on the existence of consciousness (though low) in single-celled organisms. **Mallatt, Taiz, Draguhn, Blatt and Robinson** [20], however, take issue with this hypothesis arguing that IIT attributes (degrees of) consciousness to many nonliving systems, and that if one claims that consciousness is confined to living systems IIT would not provide a good support for plant consciousness as claimed. **Vallortigara** [21] also appears skeptical about plant consciousness arguing instead that the evolutionary root to sentience should be associated with the distinction between sensation (conscious) and perception (not necessarily so), as claimed by philosopher Thomas Reid and more recently by psychologist Nicholas Humphrey [22], and he tries to outline a mechanism based on efference copy as the foundation for such a distinction and the early appearance of consciousness.

In conclusion, we firmly believe that this collection of essays provides substantial material for the development of the new emerging field of minimal cognition, and will hopefully attract new recruits to its investigation among young scientists.

Acknowledgements

We are very grateful to Prof. Ernesto Carafoli for encouraging us to submit this topic to BBRC. We would also like to thank the Special Issue Editors Dr. Olivia Nippe and Dr. Federica Burla for their constant and expert support and for managing all phases of this endeavour. Finally, we would like to add a mention to the many colleagues who accepted to comment on the manuscripts in the role of anonymous referees, and worked throughout very difficult times in the period of Summer 2020 - Spring 2021.

References

[1] Humberto R. Maturana, Francisco J. Varela, Autopoiesis and Cognition. The Realization of the Living, Reidel, Dordrecht, 1980, p. 13.
[2] Paul A. Weiss, Hierarchically Organized Systems in Theory and Practice, Knowledge, Beliefs and Freedom, Hafner Pub. Co, 1971, p. 231.
[3] Mandyam V. Srinivasan, Vision, perception, navigation and 'cognition' in honeybees and applications to aerial robotics, Biochem. Biophys. Res. Commun. (2020), https://doi.org/10.1016/j.bbrc.2020.09.052.
[4] Fiona R. Cross, Robert R. Jackson, Odour priming of a mosquito-specialist predator's vision-based detouring decisions, Biochem. Biophys. Res. Commun. (2020), https://doi.org/10.1016/j.bbrc.2020.12.005.
[5] Alexandra K. Schnell, Nicola S. Clayton, Cephalopods: ambassadors for rethinking cognition, Biochem. Biophys. Res. Commun. (2021), https://doi.org/10.1016/j.bbrc.2020.12.062.
[6] Maria Bortot, Lucia Regolin, Giorgio Vallortigara, A sense of number in invertebrates, Biochem. Biophys. Res. Commun. (2020), https://doi.org/10.1016/j.bbrc.2020.11.039.
[7] Alex M. Winsor, Guilherme F. Pagoti, Daniel J. Daye, Erik W. Cheries, Kyle R. Cave, Elizabeth M. Jakob, What gaze direction can tell us about cognitive processes in invertebrates, Biochem. Biophys. Res. Commun. (2021), https://doi.org/10.1016/j.bbrc.2020.12.001.
[8] Paco Calvo, Anthony Trewavas, Cognition and intelligence of green plants, Information for animal scientists, Biochemical and Biophysical Research Communications (2020), https://doi.org/10.1016/j.bbrc.2020.07.139.
[9] Francesco Ceccarini, Silvia Guerra, Alessandro Peressotti, Francesca Peressotti, Maria Bulgheroni, Walter Baccinelli, Bianca Bonato, Umberto Castiello, On-line control of movement in plants, Biochem. Biophys. Res. Commun. (2020), https://doi.org/10.1016/j.bbrc.2020.06.160.
[10] Björn Brembs, The brain as a dynamically active organ, Biochem. Biophys. Res. Commun. (2020), https://doi.org/10.1016/j.bbrc.2020.12.011.
[11] Antoine Wystrach, Embodiment, movements and the emergence of decisions. Insights from insect navigation, Biochem. Biophys. Res. Commun. (2021).
[12] Audrey Dussutour, Learning in single cell organisms, Biochem. Biophys. Res. Commun. (2021), https://doi.org/10.1016/j.bbrc.2021.02.018.
[13] Adam R. Gold, David L. Glanzman, The central importance of nuclear mechanisms in the storage of memory, Biochem. Biophys. Res. Commun. (2021).
[14] Samuel J. Gershman, Petra E.M. Balbi, C. Randy Gallistel, Jeremy Gunawardena, Reconsidering the evidence for learning in single cells, eLife 10 (2021), e61907, https://doi.org/10.7554/eLife.61907.
[15] Michael Levin, Life, death, and self: fundamental questions of primitive cognition viewed through the lens of body plasticity and synthetic organisms, Biochem. Biophys. Res. Commun. (2020), https://doi.org/10.1016/j.bbrc.2020.10.077.
[16] James A. Shapiro, All living cells are cognitive, Biochem. Biophys. Res. Commun. (2020), https://doi.org/10.1016/j.bbrc.2020.08.120.
[17] Arthur S. Reber, František Baluška, Cognition in some surprising places, Biochem. Biophys. Res. Commun. (2020), https://doi.org/10.1016/j.bbrc.2020.08.115.
[18] Paco Calvo, František Baluška, Trewavas Anthony, Integrated information as a possible basis for plant consciousness, Biochem. Biophys. Res. Commun. (2020), https://doi.org/10.1016/j.bbrc.2020.10.022.
[19] Giulio Tononi, Melanie Boly, Marcello Massimini, Christof Koch, Integrated information theory: from consciousness to its physical substrate, Nat. Rev. Neurosci. 17 (2016) 450–461, https://doi.org/10.1038/nrn.2016.44 pmid:27225071.
[20] Jon Mallatt, Lincoln Taiz, Andreas Draguhn, Michael R. Blatt, David G. Robinson, Integrated information theory does not make plant consciousness more convincing, Biochem. Biophys. Res. Commun. (2021), https://

doi.org/10.1016/j.bbrc.2021.01.022.
[21] Giorgio Vallortigara, The rose and the fly. A conjecture on the origin of consciousness, Biochem. Biophys. Res. Commun. (2020), https://doi.org/10.1016/j.bbrc.2020.11.005.
[22] K. Nicholas, Humphrey, *Seeing Red: A Study In Consciousness*, Belknap Press/Harvard University Press, New York, 2006.

Lucia Regolin*
Department of General Psychology, University of Padua, Padua, Italy

Giorgio Vallortigara
Centre for Mind/Brain Sciences, University of Trento, Rovereto, Italy

* Corresponding author.
E-mail address: lucia.regolin@unipd.it (L. Regolin).

Available online 26 May 2021