



OPEN

EDITORIAL

Evolution and function of neurocognitive systems in non-human animals

Elisa Frasnelli

Advances in cognitive neuroscience and neurotechnology have increased our understanding of the neurobiological mechanisms underlying cognitive processes. This Collection brings together research in animal behaviour and cognition, with studies investigating their physiology, neural mechanisms, and genetic bases, in order to provide insight into the function and evolution of neurocognitive systems.

The variety and richness of organisms found in nature offers scientists plenty of opportunities to investigate the many facets of biological complexity, and formulate novel research questions and hypotheses. This does not only apply to species-specific characteristics but, even more interestingly, to those features that can be observed across the animal kingdom. Comparative studies in psychology and neuroscience have proved to be an effective tool in advancing our understanding of the mechanisms underlying specific cognitive abilities, as well as their development, function, and evolution. This Collection gathers more than 40 contributions by scientists from all over the world, addressing different questions, in a variety of invertebrate and vertebrate species. The research comprises behavioural, electrophysiological, molecular, genetic, and neuroimaging studies, with the common aim of contributing to our understanding of the evolution and function of cognition.

Both the similarity and differences among species can help us understand the evolution of neurocognitive features and behaviours. Species as close to humans as primates enable scientists to look at brain structures and pathways (e.g., sulcal morphology¹; fast visual responses in the amygdala²) and behavioural characteristics thought to be exclusive to our species (e.g., left-cradling bias³; lateral eye bias⁴; handedness⁵; abstract concept learning⁶), and investigate their neuroanatomical, genetic, and environmental basis (e.g., mutual gaze in social communication⁷). At the same time, the study and comparison of phylogenetically distant species, like birds or fish, can be ideal for testing predictions about the generality and conservation of brain mechanisms across the evolutionary tree (e.g., inhibition of return in barn owls⁸; Approximate Number System in zebrafish⁹; numerical discrimination in domestic chicks¹⁰; visual mental manipulation in Grey parrot, children, and human adults¹¹). On the other hand, comparing related species may also reveal species-specific differences, that highlight the evolutionary divergence of neuronal circuit functions (e.g., the synaptic plasticity and the key molecules regulating it in shrews, mice, and bats¹²).

In some of the studies included in this Collection, the same tasks are presented to different species, revealing interesting inter-specific differences in the behavioural response (e.g., in re-orientation spatial skills in different species of fish¹³; in the use of geometric cues by rats and chicks¹⁴). Relatedly, comparative research of this sort sometimes raises questions about the conditions in which different species are tested. Some of the papers thus investigate potential methodological limitations in the study of animal behaviour. For instance, Morandi-Raikova and Mayer¹⁵ show that experimental manipulation can affect the behaviour and the neural activity of the tested animal. It is also essential to provide replication of previous findings, either to substantiate the claims presented, or—as done by Lemaire¹⁶ in this Collection—to question them.

Behavioural studies are extremely valuable in testing theories of adaptation (e.g., natural pedagogy in dogs¹⁷), emotional processing (e.g., in dogs¹⁸), rationality (e.g., in mice¹⁹), decision-making (e.g., in pigeons²⁰), learning (e.g., in bees²¹), and memory (e.g., in cuttlefish²²; in mice²³), but they can also reveal intriguing possible relationships, such as between behaviour, brain mass, and lifespan, as shown by Kaplan²⁴ in Australian native birds. Animals raised in laboratories give scientists the possibility to study specific cognitive abilities in naïve individuals (e.g., the use of sensory cues in social learning in naïve gerbils²⁵) and allow scientists to control for experience, especially in early life (e.g., the effect of early life stress on memory formation in the nematode *C. elegans*²⁶; the effect of long-lasting social isolation and re-socialization on cognitive performance and brain activity in *Octodon degus*²⁷). This is particularly valuable in precocial species such as chicken, which are ideal to investigate in-born

¹CIMeC Center for Mind/Brain Sciences, University of Trento, Piazza della Manifattura 1, 38068 Rovereto, TN, Italy. ²School of Life Sciences, University of Lincoln, Lincoln, Lincolnshire LN6 7DL, UK. email: elisa.frasnelli@unitn.it

predispositions to attend to specific stimuli (e.g.,²⁸), and to exploit imprinting procedures to elucidate the ecological function of statistical learning (e.g.,²⁹). Free living animals, on the other hand, allow scientists to study how species behave in their natural environment. Louder et al.³⁰ investigated behavioural plasticity and gene expression in response to different antagonistic stimuli in free-living red-winged blackbirds and found shared molecular and behavioural pathways involved in the recognition of—and reaction to—both evolutionarily old and new enemies. Wild-caught and laboratory individuals of the same species can also be tested to compare the possible group-specific performances in cognitive tasks, as shown in the study by Rössler and colleagues³¹, who investigated the ability to innovate in Goffin's cockatoos. Furthermore, through the study of groups of animals of the same species living in different habitats, it is possible to assess the effect of the environment on behaviour (e.g., the behavioural adjustment of striped field mice to human disturbance³²).

Notably, behavioural studies can be combined with molecular, electrophysiological, neuro-imaging, and genetic techniques to pinpoint the neural mechanisms underpinning behaviour (e.g., immediate early gene expression of multi-component behaviour in pigeons³³; protein products of the immediate early genes in response to exposure to conspecific contact calls in male budgerigars³⁴; electrophysiological recordings of neuronal activity during song broadcast and social relationships in starlings³⁵; cortical activity and motor behaviour to establish levels of arousal in rodents³⁶). Furthermore, they can be used to investigate the effects of a treatment on behaviour (e.g., chronic consumption of D-amino acids on spatial learning and expression of NMDA receptors in mice³⁷) and on their neural signature (e.g., anxiolytic high-frequency electrical stimulation of the bed nucleus of the stria terminalis in rats on c-Fos expression³⁸). Some species can be manipulated so that they express a marker such as GFP, in specific subpopulations of neurons, in order to study their differentiation and development (e.g., sex-differences in hippocampal neurons in mice³⁹); whereas in other species, genetic lines in which a particular gene is silenced can be produced, which is invaluable for providing insights into the genetic substrates of specific neurobiological features or behaviours (e.g., lateralization in *Drosophila*⁴⁰; impulsivity in rats⁴¹).

The papers published in this Collection highlight how fundamental studies on animal models are to our understanding of the functioning, development, and evolution of neurocognitive systems, and teach us, through the comparative approach, that we share more than we think with even the more evolutionarily distant species.

Published online: 08 December 2021

References

1. Miller, J. A. *et al.* Sulcal morphology of ventral temporal cortex is shared between humans and other hominoids. *Sci. Rep.* **10**, 17132. <https://doi.org/10.1038/s41598-020-73213-x> (2020).
2. Cleeren, E. *et al.* Fast responses to images of animate and inanimate objects in the nonhuman primate amygdala. *Sci. Rep.* **10**, 14956. <https://doi.org/10.1038/s41598-020-71885-z> (2020).
3. Boulinguez-Ambroise, G. *et al.* Human-like maternal left-cradling bias in monkeys is altered by social pressure. *Sci. Rep.* **10**, 11036. <https://doi.org/10.1038/s41598-020-68020-3> (2020).
4. Donati, G., Davis, R. & Forrester, G. S. Gaze behaviour to lateral face stimuli in infants who do and do not receive an ASD diagnosis. *Sci. Rep.* **10**, 13185. <https://doi.org/10.1038/s41598-020-69898-9> (2020).
5. Forrester, G. S. *et al.* Evolutionary motor biases and cognition in children with and without autism. *Sci. Rep.* **10**, 17385. <https://doi.org/10.1038/s41598-020-74224-4> (2020).
6. Rugani, R. *et al.* Middle identification for rhesus monkeys is influenced by number but not extent. *Sci. Rep.* **10**, 17402. <https://doi.org/10.1038/s41598-020-74533-8> (2020).
7. Hopkins, W. D. *et al.* The role of early social rearing, neurological, and genetic factors on individual differences in mutual eye gaze among captive chimpanzees. *Sci. Rep.* **10**, 7412. <https://doi.org/10.1038/s41598-020-64051-y> (2020).
8. Lev-Ari, T. *et al.* Behavioral and neuronal study of inhibition of return in barn owls. *Sci. Rep.* **10**, 7267. <https://doi.org/10.1038/s41598-020-64197-9> (2020).
9. Messina, A. *et al.* Response to change in the number of visual stimuli in zebrafish: A behavioural and molecular study. *Sci. Rep.* **10**, 5769. <https://doi.org/10.1038/s41598-020-62608-5> (2020).
10. Rugani, R. *et al.* Individually distinctive features facilitate numerical discrimination of sets of objects in domestic chicks. *Sci. Rep.* **10**, 16408. <https://doi.org/10.1038/s41598-020-73431-3> (2020).
11. Pailian, H. *et al.* Age and species comparisons of visual mental manipulation ability as evidence for its development and evolution. *Sci. Rep.* **10**, 7689. <https://doi.org/10.1038/s41598-020-64666-1> (2020).
12. Beed, P. *et al.* Species-specific differences in synaptic transmission and plasticity. *Sci. Rep.* **10**, 16557. <https://doi.org/10.1038/s41598-020-73547-6> (2020).
13. Sovrano, V. A. *et al.* The geometry as an eyed fish feels it in spontaneous and rewarded spatial reorientation tasks. *Sci. Rep.* **10**, 8020. <https://doi.org/10.1038/s41598-020-64690-1> (2020).
14. Lee, S. A. *et al.* Distinct and combined responses to environmental geometry and features in a working-memory reorientation task in rats and chicks. *Sci. Rep.* **10**, 7508. <https://doi.org/10.1038/s41598-020-64366-w> (2020).
15. Morandi-Raikova, A. & Mayer, U. The effect of monocular occlusion on hippocampal c-Fos expression in domestic chicks (*Gallus gallus*). *Sci. Rep.* **10**, 7205. <https://doi.org/10.1038/s41598-020-64224-9> (2020).
16. Lemaire, B. S. No evidence of spontaneous preference for slowly moving objects in visually naïve chicks. *Sci. Rep.* **10**, 6277. <https://doi.org/10.1038/s41598-020-63428-3> (2020).
17. Neilands, P., Kingsley-Smith, O. & Taylor, A. H. Dogs' insensitivity to scaffolding behaviour in an A-not-B task provides support for the theory of natural pedagogy. *Sci. Rep.* **11**, 860. <https://doi.org/10.1038/s41598-020-79557-8> (2021).
18. Bolló, H. *et al.* REM versus non-REM sleep disturbance specifically affects inter-specific emotion processing in family dogs (*Canis familiaris*). *Sci. Rep.* **10**, 10492. <https://doi.org/10.1038/s41598-020-67092-5> (2020).
19. Schneider, N. A. *et al.* Parametric shift from rational to irrational decisions in mice. *Sci. Rep.* **11**, 480. <https://doi.org/10.1038/s41598-020-79949-w> (2021).
20. Manns, M., Otto, T. & Salm, L. Pigeons show how meta-control enables decision-making in an ambiguous world. *Sci. Rep.* **11**, 3838. <https://doi.org/10.1038/s41598-021-83406-7> (2021).
21. Aguiar, J. M. R. B. V., Giurfa, M. & Sazima, M. A cognitive analysis of deceptive pollination: Associative mechanisms underlying pollinators' choices in non-rewarding colour polymorphic scenarios. *Sci. Rep.* **10**, 9476. <https://doi.org/10.1038/s41598-020-66356-4> (2020).

22. Billard, P., Clayton, N. S. & Jozet-Alves, C. Cuttlefish retrieve whether they smelt or saw a previously encountered item. *Sci. Rep.* **10**, 5413. <https://doi.org/10.1038/s41598-020-62335-x> (2020).
23. Cruz-Sanchez, A. *et al.* Developmental onset distinguishes three types of spontaneous recognition memory in mice. *Sci. Rep.* **10**, 10612. <https://doi.org/10.1038/s41598-020-67619-w> (2020).
24. Kaplan, G. Play behaviour, not tool using, relates to brain mass in a sample of birds. *Sci. Rep.* **10**, 20437. <https://doi.org/10.1038/s41598-020-76572-7> (2020).
25. Paraouty, N., Charbonneau, J. A. & Sanes, D. H. Social learning exploits the available auditory or visual cues. *Sci. Rep.* **10**, 14117. <https://doi.org/10.1038/s41598-020-71005-x> (2020).
26. Gece, E. *et al.* A cellular defense memory imprinted by early life toxic stress. *Sci. Rep.* **9**, 18935. <https://doi.org/10.1038/s41598-019-55198-4> (2019).
27. Rivera, D. S. *et al.* Effects of long-lasting social isolation and re-socialization on cognitive performance and brain activity: A longitudinal study in *Octodon degus*. *Sci. Rep.* **10**, 18315. <https://doi.org/10.1038/s41598-020-75026-4> (2020).
28. Versace, E., Ragusa, M. & Vallortigara, G. A transient time window for early predispositions in newborn chicks. *Sci. Rep.* **9**, 18767. <https://doi.org/10.1038/s41598-019-55255-y> (2019).
29. Santolin, C. *et al.* Statistical learning in domestic chicks is modulated by strain and sex. *Sci. Rep.* **10**, 15140. <https://doi.org/10.1038/s41598-020-72090-8> (2020).
30. Louder, M. I. M. *et al.* Shared transcriptional responses to con- and heterospecific behavioral antagonists in a wild songbird. *Sci. Rep.* **10**, 4092. <https://doi.org/10.1038/s41598-020-60231-y> (2020).
31. Rössler, T. *et al.* Using an Innovation Arena to compare wild-caught and laboratory Goffin's cockatoos. *Sci. Rep.* **10**, 8681. <https://doi.org/10.1038/s41598-020-65223-6> (2020).
32. Dammhahn, M. *et al.* Of city and village mice: Behavioural adjustments of striped field mice to urban environments. *Sci. Rep.* **10**, 13056. <https://doi.org/10.1038/s41598-020-69998-6> (2020).
33. Rook, N. *et al.* Immediate early gene fingerprints of multi-component behaviour. *Sci. Rep.* **10**, 384. <https://doi.org/10.1038/s41598-019-56998-4> (2020).
34. Satoh, R. *et al.* Memory-specific correlated neuronal activity in higher-order auditory regions of a parrot. *Sci. Rep.* **11**, 1618. <https://doi.org/10.1038/s41598-020-80726-y> (2021).
35. Cousillas, H. *et al.* Lateralization of social signal brain processing correlates with the degree of social integration in a songbird. *Sci. Rep.* **10**, 14093. <https://doi.org/10.1038/s41598-020-70946-7> (2020).
36. Gao, S. & Calderon, D. P. Robust alternative to the righting reflex to assess arousal in rodents. *Sci. Rep.* **10**, 20280. <https://doi.org/10.1038/s41598-020-77162-3> (2020).
37. Zachar, G. *et al.* D-Aspartate consumption selectively promotes intermediate-term spatial memory and the expression of hippocampal NMDA receptor subunits. *Sci. Rep.* **11**, 6166. <https://doi.org/10.1038/s41598-021-85360-w> (2021).
38. Luyck, K. *et al.* c-Fos expression following context conditioning and deep brain stimulation in the bed nucleus of the stria terminalis in rats. *Sci. Rep.* **10**, 20529. <https://doi.org/10.1038/s41598-020-77603-z> (2020).
39. Brandt, N. *et al.* Sex-specific features of spine densities in the hippocampus. *Sci. Rep.* **10**, 11405. <https://doi.org/10.1038/s41598-020-68371-x> (2020).
40. Versace, E. *et al.* Individual, but not population asymmetries, are modulated by social environment and genotype in *Drosophila melanogaster*. *Sci. Rep.* **10**, 4480. <https://doi.org/10.1038/s41598-020-61410-7> (2020).
41. Jupp, B. *et al.* Impulsivity is a heritable trait in rodents and associated with a novel quantitative trait locus on chromosome 1. *Sci. Rep.* **10**, 6684. <https://doi.org/10.1038/s41598-020-63646-9> (2020).

Competing interests

The author declares no competing interests.

Correspondence and requests for materials should be addressed to E.F.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

© The Author(s) 2021