Has evolution learnt how to learn?

The two-hundredth anniversary of Charles Darwin's birth has been a cause for celebration and reflection about the theory of evolution: one of the most powerful ideas in history, the full dimensions of which are still being explored. Darwin's genius was to describe a simple mechanism to account for the generation of biological diversity and the history of life, arising from the interplay between individual variation and the competition among individuals for survival and reproduction, with those that are best adapted to their environment, or able to colonize new niches, being successful. This blind process, described as a grinding algorithm by Daniel Dennett (Dennett, 1995), led inexorably to the emergence of developmentally complex organisms, including species capable of learning, cognition and, ultimately, self-reflection.

Indeed, cognition must be an eventual outcome of the evolutionary process, albeit with a highly contingent history. While it is an advantage to evolve particular metabolic capacities or physical characteristics, it is also an advantage to be able to collect information about the environment and to act on this information to increase the odds of survival and reproduction, especially for those species capable of movement and dexterity. One can trace an evolutionary path from microbial chemosensory proteins, which are connected through signal transduction cascades to motility systems, to olfactory, tactile, visual and aural systems in animals, accompanied by ever more sophisticated circuitry to process such information. Many species, notably birds and mammals, but also invertebrates such as the octopus, have progressed to varying extents along the pathway to more advanced cognitive capabilities.

Importantly, cognitive function and memory are connected to epigenetic processes, which, although the mechanisms are uncertain, increasingly appear to be RNA-directed. Moreover, the brain is also the main site for RNA editing—the post-transcriptional alteration of RNA sequences by adenosine

and cytosine deamination—which is far more widespread than generally appreciated, and which has expanded enormously in humans. Thus, RNA might not only be the computational engine of the cell, but also a major conduit for gene–environment interactions, which might, in turn, feed back into epigenetic memory (Mattick *et al*, 2009).

If the ability to learn and adapt in real time comprises a selective advantage, would it not also be a selective advantage to use experience to alter the behaviour or physical capabilities of their progeny? That is, if a mechanism could evolve to allow the inheritance of useful characteristics or information acquired by interaction with the environment, would that not be an advantage to evolution itself? Surely the answer, in principle, is yes—even if by no other means than the use of advanced behaviours or cognitive abilities to educate the young, or to modify the environment and ultimately one's own genetic material.

Which brings us to Jean-Baptiste de Lamarck, whose own book on evolution, *Philosophie Zoologique*, was published shortly before Darwin's birth. Lamarck proposed that organisms evolve by a process of adaptation through the use and disuse of characteristics, and by an alchemical 'complexifying force'. However, Lamarck, unlike Darwin, did not propose a mechanism for how this might occur, although one might generously argue that the 'complexifying force' was simply meant to describe the opportunity to explore niches available to more complex organisms. In any case, although Lamarck's ideas of evolution by learnt adaptation, rather than by selection, have been widely rejected in favour of the more fundamental and compelling explanation offered by Darwin, their hypotheses are not mutually exclusive. The ability to transmit a memory of adaptation to experience would be not only subject to natural selection, but also potentially favoured by it.

Recent findings suggest that this might occur and that all of the mechanisms required are either in place or possible. There is now evidence for RNA-directed non-Mendelian epigenetic inheritance ('paramutation') in plants and animals (Chandler, 2007). This

makes some sense because it might be preferable for bequeathed information to be plastic, rather than hard-wired. Whether this involves a breach of the Weissman barrier, which proposes that changes to the genetic material in somatic cells cannot be transmitted to the germline, is a moot point. However, it seems that RNA can be transported intercellularly and systemically in both plants and animals (Dinger *et al*, 2008), thus providing a potential means for transmitting epigenetic information. Intriguingly, there is both a blood–brain and a blood–testis barrier in mammals, indicating that both tissues are similarly privileged, but how this might be interpreted in terms of RNA-mediated informational transactions is uncertain. It is also uncertain whether RNA-directed epigenetic information could ultimately be fixed in the DNA. None of the inherited epigenetic changes documented so far have been accompanied by changes to the underlying DNA sequence, but RNA-directed DNA repair enzymes have been found in simple eukaryotes, and there are transposon-encoded reverse transcriptases and odd DNA repair enzymes that seem to have reverse transcriptase activity encoded in the mammalian genome (Mattick & Mehler, 2008).

This is not to suggest that Lamarckian-style inheritance occurs, but simply that there is no reason to exclude the possibility, and some evidence—as well as logic—to suggest that it is plausible. It remains a tantalizing question.

REFERENCES

- Chandler VL (2007) Paramutation: from maize to mice. *Cell* **128**: 641–645
Dennett D (1995) *Darwin's Dangerous Idea: Evolution and the Meanings of Life*, New York, NY, USA: Simon Schuster
Dinger ME, Mercer TR, Mattick JS (2008) RNAs as extracellular signaling molecules. *J Mol Endocrinol* **40**: 151–159
Mattick JS, Amaral PP, Dinger ME, Mercer TR, Mehler MF (2009) RNA regulation of epigenetic processes. *Bioessays* **31**: 51–59
Mattick JS, Mehler MF (2008) RNA editing, DNA recoding and the evolution of human cognition. *Trends Neurosci* **31**: 227–233

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