

the presence of viral footprints such as interferons and increased MHC-I expression. If viral infection proves to be a contributing factor, we could aim to lower the risk of type 1 diabetes by designing suitable vaccines against human enteroviruses. ■

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- Redondo, M. J., Jeffrey, J., Fain, P. R., Eisenbarth, G. S. & Orban, T. N. *Engl. J. Med.* **359**, 2849–2850 (2008).
- Nejentsev, S., Walker, N., Riches, D., Egholm, M. & Todd, J. A. *Science* **324**, 387–389 (2009).

- Green, J., Casabonne, D. & Newton, R. *Diabet. Med.* **21**, 507–514 (2004).
- Kanno, T. *et al. J. Virol.* **80**, 5637–5643 (2006); Erratum *J. Virol.* **80**, 8843 (2006).
- Filippi, C. M., Estes, E. A., Oldham, J. E. & von Herrath, M. G. *J. Clin. Invest.* (in the press).
- Eizirik, D. L., Colli, M. L. & Ortis, F. *Nature Rev. Endocrinol.* **5**, 219–226 (2009).
- Seewaldt, S. *et al. Diabetes* **49**, 1801–1809 (2000).
- von Herrath, M. G., Fujinami, R. S. & Whitton, J. L. *Nature Rev. Microbiol.* **1**, 151–157 (2003).
- Pipeleers, D. *et al. Novartis Found. Symp.* **292**, 19–24; discussion 24–31, 122–129, 202–203 (2008).
- Skowera, A. *et al. J. Clin. Invest.* **118**, 3390–3402 (2008).
- Dotta, F. *et al. Proc. Natl Acad. Sci. USA* **104**, 5115–5120 (2007).
- Richardson, S. J., Willcox, A., Bone, A. J., Foulis, A. K. & Morgan, N. G. *Diabetologia* **52**, 1143–1151 (2009).
- Liu, S. *et al. Hum. Mol. Genet.* **18**, 358–365 (2009).
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ANIMAL BEHAVIOUR

Birdsong normalized by culture

W. Tecumseh Fitch

Both birdsong and human language are learned, requiring complex social input. New findings show, however, that bird populations ‘seeded’ with aberrant song input transform it to normal song in a few generations.

Around 650 BC, the Egyptian king Psammeticus reputedly had two children raised by a mute goatherd, isolated from all linguistic input, to determine what language they would speak spontaneously¹. As legend has it, the children’s first word was *bekos*, so the king judged the ‘original language’ to be Phrygian, in which *bekos* means bread (that *bekos* represented the bleat of a goat was apparently not considered). Today, such an experiment seems both unethical and naive, for we know from numerous examples that children deprived of linguistic input will not spontaneously speak any language. To acquire language, humans need rich linguistic input early in life^{2,3}. In a study published on page 564 of this issue, Fehér and colleagues⁴ greatly improve on Psammeticus’s experiment, using laboratory-raised songbirds.

When isolated from normal input, humans develop only basic communication systems. Deaf children raised in hearing homes spontaneously create simple communication systems termed home-sign⁵. Lacking semantic and grammatical complexity, such systems cater only to simple, specific needs. Similarly, adults thrown together with no common language develop pidgins — communication systems with small vocabularies and simple grammar. But intriguingly, in both cases, later generations transform such simple systems into true languages, with a full range of grammatical expressiveness. Pidgins can become complex, stable languages known as creoles in just a few generations^{6,7}: in Nicaragua, deaf children transformed a set of simple home-sign systems into the full Nicaraguan sign language (NSL) within a few decades, under the

watchful eyes and video cameras of linguists⁸.

But such fascinating examples raise more questions than they answer. Do the systems developed by isolated children reflect an original, biologically given form of language, as Psammeticus believed? Or is cultural transmission itself a necessary part of human language? Do children require rich lexical and grammatical input to fully activate the language-acquisition system? How do the neural networks underlying isolated languages such as home-sign differ from those that mediate communication with full languages? For ethical reasons, linguists cannot address these questions with controlled experiments, and interpretations of ‘natural experiments’ such as NSL remain controversial. A more biologically tractable model of cultural transmission is therefore needed.

One possibility involves investigating birdsong. Biologists have known since Darwin’s time that, to sing properly, young songbirds require song input, typically during an early sensitive period preceding adulthood⁹. Deprived of such input, they sing only an abnormal song, with fewer syllable types and less structure than normal.

Darwin further recognized that learned birdsong nullifies traditional nature/nurture dichotomies. Birdsong is neither an instinct present at birth, nor an arbitrary cultural construction: it rests on biological foundations, but also requires specific inputs to develop properly. Songs are transmitted and transformed over several generations of learners, forming birdsong ‘dialects’ that vary geographically within a species¹⁰. Thus, both birdsong and language are generated by a species-typical ‘instinct to learn’ that constrains, but does not

fully determine, the final outcome¹¹. Birdsong acquisition provides, in this sense, an animal equivalent of human cultural transmission.

In their study, Fehér *et al.*⁴ first raise young male zebra finches in isolation. At adulthood, these birds sing only a raspy, arrhythmic isolate (ISO) song. The authors then pair these adult male ‘tutors’ with young males. These first-generation young learners successfully imitate ISO song, but already begin to transform it in the direction of normal — wild-type — song. Iterating this process, using first-generation song as input to a second generation of birds and so on, the authors follow the birds for up to five generations and find that each generation’s song moves steadily closer to normal zebra finch song.

Fehér and colleagues performed these initial experiments with otherwise-isolated males, tutored one-on-one. To explore the consequences of a more typical social environment, the authors⁴ established a colony of females, socially housed and seeded with a single ISO male. Again, the songs of the descendant males transformed steadily in the direction of normal song. Intriguingly, however, these learner males’ songs also incorporated their male siblings’ song errors and female whistles. This ‘cultural’ experimental condition is more reminiscent of human sign languages such as NSL, in which a critical mass of young signers is needed to spark the development of a rich lexicon and grammatical complexity typical of true human language¹².

Of course, zebra-finch song is not language: birdsong is not used to express complex meanings; has only a simple syntax; and is typically produced only by males. But the techniques and model Fehér and colleagues introduce exploit a mechanism — cultural transmission of vocally learned signals — shared by both systems^{13,14}. This new approach will allow detailed mechanistic explorations into how iterating the process of song acquisition can lead to something more diverse and structured than any individual bird creates on its own. What are the differences in brain circuitry between ISO birds and their fourth-generation descendants? In later generations, will we see better-developed song circuitry, or different activation patterns of the genes involved in vocal learning? What about females: do they prefer normal song, regardless of their upbringing, or does song resembling their father’s ISO song excite them more?

Ultimately, addressing these issues will allow us to uncover the detailed biological bases of songbirds’ instinct to learn song. If discoveries concerning genetic similarities in birdsong and human speech¹⁵ are any guide, such work may also provide intriguing hints about the biological mechanisms underlying the language-acquisition system in humans. Thus, Fehér and colleagues’ birdsong studies provide a pioneering approach for exploring the biology of culturally transmitted systems in the laboratory. ■

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1. Herodotus *The Histories* (Penguin, 1964).
2. Lenneberg, E. H. *Biological Foundations of Language* (Wiley, 1967).
3. Kuhl, P. K. *Nature Rev. Neurosci.* **5**, 831–843 (2004).
4. Fehér, O., Wang, H., Saar, S., Mitra, P. P. & Tchernichovski, O. *Nature* **459**, 564–568 (2009).
5. Goldin-Meadow, S. & Mylander, C. *Nature* **391**, 279–281 (1998).
6. Mühlhäusler, P. *Pidgin and Creole Linguistics* revised edn (Univ. Westminster Press, 1997).

7. Sandler, W., Meir, I., Padden, C. & Aronoff, M. *Proc. Natl Acad. Sci. USA* **102**, 2661–2665 (2005).
8. Senghas, A., Kita, S. & Özyürek, A. *Science* **305**, 1779–1782 (2004).
9. Darwin, C. *The Descent of Man, and Selection in Relation to Sex* 1st edn (John Murray, 1871).
10. Marler, P. & Slabbekoorn, H. *Nature's Music: The Science of Birdsong* (Academic, 2004).
11. Marler, P. in *The Epigenesis of Mind: Essays on Biology and Cognition* (eds Carey, S. & Gelman, R.) 37–66 (Lawrence Erlbaum Associates, 1991).
12. Senghas, A. & Coppola, M. *Psychol. Sci.* **12**, 323–328 (2002).
13. Jarvis, E. D. *Ann. NY Acad. Sci.* **1016**, 749–777 (2004).
14. Nottebohm, F. *Ann. NY Acad. Sci.* **280**, 643–649 (1976).
15. Haesler, S. et al. *PLoS Biol.* **5**, e321 (2007).

EARTH SCIENCE

Restoration of the noble gases

Tim Elliott

The noble gases emitted from deep inside the Earth have been sending mixed messages to those intent on deciphering them. A model that promises to help clear up the confusion is now on offer.

Geochemists have long taken a close interest in emissions from the bowels of the Earth. In particular, analyses of noble gases emanating from the mantle have been prominent in shaping models of Earth's structure. Lately, these data have seemed to be more paradoxical than illuminating, but Gonnermann and Mukhopadhyay (page 560 of this issue)¹ have revisited this puzzle and, by adding a new twist to an old concept, help us come to terms again with our planet's gassy innards.

Gas is continuously lost from Earth's interior, being carried to the surface in magmas produced by melting of the shallow mantle. The abundances and isotopic compositions of the trace amounts of noble gases thus erupted provide clues to Earth's evolution. In this field of study, the natural isotopic variability of helium has had an especially influential role. Helium has two stable isotopes, ³He and ⁴He. Earth's complement of ³He was acquired during the planet's formation, whereas ⁴He has been produced throughout Earth's history by the decay of the naturally occurring radionuclides of uranium and thorium. Thus, the ⁴He/³He ratio increases with time, with a magnitude dependent on the (U+Th)/He ratio.

It is well established that the ⁴He/³He ratios of magma from many ocean islands (such as Hawaii) are significantly lower than those of magma erupted at submarine mid-oceanic ridges. This observation has been thought to reflect 'degassing' of the upper mantle as a result of melting and crust formation at mid-oceanic ridges, driven by the spreading of tectonic plates (Fig. 1a). Magma transports helium, uranium and thorium from the mantle to the surface. Although helium is ultimately lost to the atmosphere, non-volatile uranium and thorium remain in the crust to be subsequently returned to the mantle by plate subduction. Hence, the

mantle involved in the plate-tectonic cycle attains a higher (U+Th)/He ratio and so evolves to higher ⁴He/³He ratios than any unmolested, 'primitive' mantle. The low ⁴He/³He ratio evident in some ocean islands was thus taken to reflect their derivation from such a primitive source that had been convectively isolated from the rest of the mantle. This meshed with the idea that ocean islands are the surface manifestation of mantle plumes that, like the wax in lava lamps, rise by thermal buoyancy from a deep, hot boundary layer (Fig. 1b).

Imagination can be allowed to run further

riot within this conceptually appealing model. Early estimates of the composition of the continental crust suggested that it might have been derived from melting of the upper third of the mantle. This fraction spookily corresponds to the proportion of the mantle above a notable seismic feature at a depth of 660 kilometres. So the notion of a layered mantle was born, with the 660-km discontinuity dividing 'depleted' upper mantle from 'primitive' lower mantle (Fig. 2a). The calling card of the lower mantle was its low ⁴He/³He ratio, and this ratio acquired a mystical significance, such that it is even traditionally expressed in the opposite way to all other radiogenic isotope ratios (that is, as ³He/⁴He, with the isotope produced by radioactive decay in the denominator).

Although the layered-mantle model also helped to account for a series of other notable observations of noble gases (refs 2, 3, for example), it has proved inconsistent with geochemical constraints provided by much of the rest of the periodic table. There is little evidence for any extant primitive mantle as assessed from a wide range of non-volatile element abundance and isotope ratios (ref. 4, for example). Moreover, seismological studies convincingly demonstrated⁵ that the 660-km discontinuity is not a boundary to mantle flow, and so the notion that primitive mantle can be preserved in the lower mantle became untenable (Fig. 2b). Thus, some researchers^{6,7} have argued for an entirely different mechanism for creating low ⁴He/³He ratios in the mantle. Yet noble-gas mythology is deep-rooted, and others have rebranded the layered mantle with a deeper boundary⁸, or suggested that we live in a unique time in which long-term layering has only just been breached⁹. So it has increasingly seemed that noble-gas

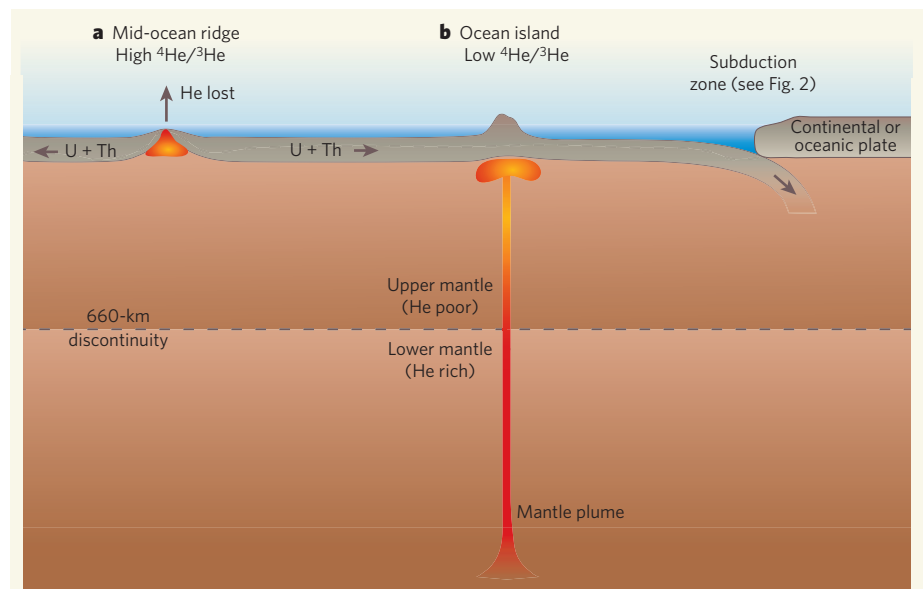


Figure 1 | Isotope ratios and Earth's mantle. **a**, As oceanic plates are pulled apart at mid-oceanic ridges, the upper mantle rises in their place and (partially) melts. Uranium, thorium and helium in this portion of mantle are transferred to the magma, which migrates to the surface to form crust. Helium is lost during crystallization of the melts, but uranium and thorium are retained in the crust and are ultimately returned to the mantle by plate subduction (Fig. 2). Thus, the upper mantle becomes 'degassed' and the (U+Th)/He ratio increases, which with time translates into higher ⁴He/³He ratios. **b**, By contrast, ocean islands show a low ⁴He/³He ratio, thought to reflect a deep-mantle source of underlying mantle plumes. Graphic not to scale.