et al. demonstrate that the 18-kb element in *V. cholerae* also circularizes after phage infection, and that it encodes an active anti-phage system. Consequently, the authors refer to it as a PICI-like element, or PLE.

Further studies of one of the isolated phages, which carried a CRISPR/Cas system with two PLE-targeting spacers, showed that it could replicate and kill a PLE-harbouring *V. cholerae* strain that had been isolated from the same stool sample. However, Seed and colleagues show that a mutant version of this phage that lacks the matching spacer cannot replicate in the PLE-harbouring strain, but can replicate in a mutated *V. cholerae* strain lacking the PLE, further supporting the targeted action of the system.

The authors also performed an elaborate set of experiments to confirm the hallmarks of an active CRISPR/Cas system. For example, they show that crRNAs are transcribed and processed from the phages, and that derivative phages that have acquired new CRISPR spacers targeting the PLE can be isolated. Overall, these results demonstrate that phages can hijack a functional, adaptive immune-evasion system to benefit their own multiplication. And, as stated by the authors, because bacterial cell death and DNA damage are inherent in virulent phage infection, CRISPR-mediated DNA cleavage of the targeted bacterial genome does not have a negative impact on phage proliferation.

Seed and colleagues' study illustrates another extraordinary turn of events in the evolution of phages and bacteria, in which the phages defeat the bacteria outright by using one of its own weapons against it. How frequently such an event occurs and whether a phage that contains a CRISPR/Cas system stays stable remains to be seen. Nevertheless, these findings will certainly fuel selected applications. For example, the discovery of other phages with a CRISPR/Cas system that targets host genes or more phages with anti-CRISPR genes[8] may provide additional leverage to design an efficient cocktail of natural or engineered phages to prevent or treat bacterial contamination or infection. On the other hand, this finding suggests that biotechnological industries that rely solely on CRISPR/Cas systems to protect key bacterial strains from phage infection should be ready to go back to the drawing board. Because, as always, phages will find a way. They may already have. ■

Manuela Villion *and* **Sylvain Moineau** *are in the Département de biochimie, microbiologie et bio-informatique, Faculté des sciences et de génie, Université Laval, Québec G1V 0A6, Canada.* **S.M.** *is also in the Groupe de recherche en écologie buccale, Faculté de médecine dentaire, and the Félix d'Hérelle Reference Center for Bacterial Viruses, Université Laval.*
e-mail : sylvain.moineau@bcm.ulaval.ca

1. Suttle, C. A. *Nature* **437,** 356–361 (2005).
2. Labrie, S. J., Samson, J. E. & Moineau, S. *Nature Rev. Microbiol.* **8,** 317–327 (2010).
3. Barrangou, R. *et al. Science* **315,** 1709–1712 (2007).
4. Seed, K. D., Lazinski, D. W., Calderwood, S. B. & Camilli, A. **494,** 489–491 (2013).
5. Wiedenheft, B., Sternberg, S. H. & Doudna, J. A. *Nature* **482,** 331–338 (2012).
6. Garneau, J. E. *et al. Nature* **468,** 67–71 (2010).
7. Deveau, H. *et al. J. Bacteriol.* **190,** 1390–1400 (2008).
8. Bondy-Denomy, J., Pawluk, A., Maxwell, K. L. & Davidson, A. R. *Nature* **493,** 429–432 (2013).
9. Minot, S. *et al. Genome Res.* **21,** 1616–1625 (2011).
10. World Health Organization. *Wkly Epidemiol. Rec.* **87,** 289–304 (2012).
11. Novick, R. P., Christie, G. E. & Penadés, J. R. *Nature Rev. Microbiol.* **8,** 541–551 (2010).
12. Ram G. R. *et al. Proc. Natl Acad. Sci. USA* **109,** 16300–16305 (2012).

SPEECH SCIENCE

Tuned to the rhythm

Rhesus macaques' responses to computer-animated images of lip-smacking monkey faces suggest that the jaw, tongue and lip oscillations that characterize human speech may have evolved from rhythmic primate facial expressions.

W. TECUMSEH FITCH

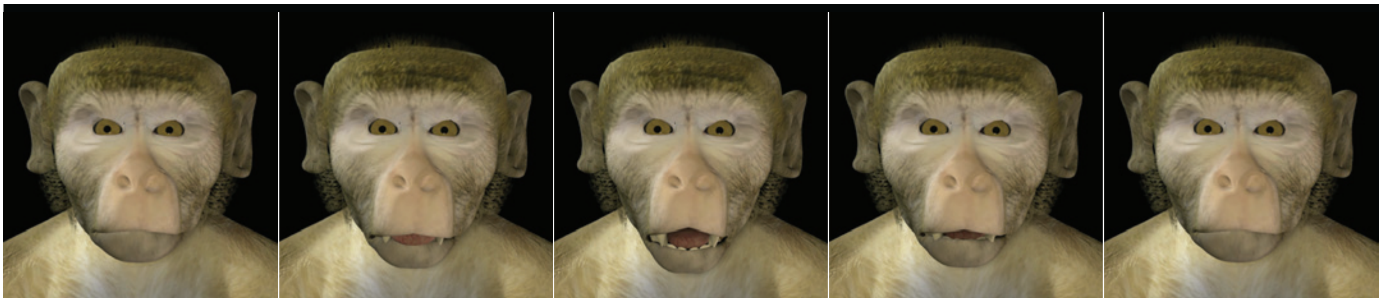
Language is a multifaceted jewel, with some facets better studied than others. Although the evolution of syntax and vowel production is much discussed, other aspects of spoken language remain relatively neglected. In particular, the origins of the periodic oscillations that produce the alternation of consonants and vowels that make up syllables — a central feature of all spoken languages — have remained mysterious, because most primate calls are produced with just a single opening of the mouth. Writing in *Proceedings of the National Academy of Sciences*, Ghazanfar and colleagues[1] offer an intriguing perspective on this question by studying a class of visual display, termed lip-smacking, that is found in many non-human primates. The authors show that rhesus macaques are 'tuned' to a natural lip-smacking frequency range that is similar to the oscillation frequency of speech, supporting the hypothesis that the origin of human speech rhythms lies not in ancestral primate vocal displays, but rather in rhythmic facial expressions.

The jaw, tongue and lip oscillations in human speech occur at roughly six times per second (6 hertz), and speech perception is optimal when syllable rates flow in this natural rhythm[2,3]. Ghazanfar *et al.* tested whether the same is true for monkeys, whose natural lip-smacking rhythm occupies a similar 3–8-Hz frequency range. The authors offered rhesus macaque 'viewers' a choice between two computer-animated lip-smacking displays: one at 6 Hz and another at an abnormally fast or slow rate (Fig. 1). They found that macaques spent more time watching the 6-Hz animations. What's more, many of the monkeys lip-smacked back to the monitor, showing that they indeed interpreted the monkey avatar's behaviour as lip-smacking. These results show a clear and convincing preference for natural-rate monkey facial movements. However, their significance for speech evolution may be less obvious.

There are two main hypotheses for the evolutionary origin of human speech[4]. The first and most widespread is that speech is derived from primate vocalizations, which were harnessed or co-opted to convey linguistic information. In support of this idea, the same vocal production system (lungs, larynx and vocal tract) is used to produce both primate calls and speech. A problem is that human speech is unique among primate vocalizations in being a very flexible, learned signal, whereas most primate calls have a strong, species-specific genetic determination. The 'vocal origins' hypothesis favours evolutionary continuity of vocal production over a hypothetical discontinuity in vocal control and vocal learning.

The second, and less intuitive, hypothesis builds on the fact that the lips, jaws and tongue generate not just vocal, but also visual, signals — and, unlike the larynx, these articulators are under learned voluntary control in non-human primates. This led evolutionary neuroscientist Peter MacNeilage to suggest[5] that speech rhythms originated not in the vocal but in the visual domain. In a sense, he argued, speech starts out (in babies' babbling, for example) as a lip-smacking oscillation superimposed on a vocal signal. This rhythmic stream is then differentially modified, by learned tongue and lip movements, into the vowels and consonants of speech. Support for this hypothesis comes from previous work demonstrating that the detailed kinematics of lip-smacking are strikingly similar to those of speech[6]. But Ghazanfar and colleagues' work adds support from the domain of perception, indicating that perceptual tuning for the two signal classes is also consistent with MacNeilage's hypothesis.

The approach pioneered by Ghazanfar *et al.*



REF. 1

Figure 1 | From the mouths of monkeys. A frame sequence from a video clip of computer-simulated monkey faces producing lip-smacking movements that Ghazanfar *et al.*[1] showed to rhesus macaques. The authors compared the macaques' responses to lip-smacking at their natural 6-hertz rhythm, which matches the syllable rate of human speech, with lip-smacking at faster (10 Hz) or slower (3 Hz) frequencies.

offers many possibilities for further work. Particularly intriguing would be to attempt the same procedure with chimpanzees. A positive result in this or other primate species would increase the chance that 6-Hz lip-smack tuning is shared by common descent in many primates. Equally interesting will be to explore whether watching lip-smacking evokes synchronized neuronal oscillations in the visual cortex. A major advantage of studying macaques over humans is that neuroscientists can perform both brain imaging and direct recording of cortical-neuron activity[7]. This would allow the neural processes underlying such rhythms to be investigated in greater detail.

If accumulating evidence ends up supporting MacNeilage's hypothesis, it will have fascinating implications for the evolution of spoken language. A long tradition has focused on details of human vocal-tract anatomy — in particular, our descended larynx — as a key prerequisite for human speech. But many studies suggest that the importance of anatomy has been overestimated, and that factors of neural control are dominant[4]. Humans have a uniquely well-developed capacity for vocal learning, which entailed forging new neural links between the auditory cortex and the motor cortex[8]. MacNeilage's hypothesis suggests that the evolutionary route by which these links were formed was circuitous, and initially involved co-opting visual-communication circuitry that was already present and under voluntary cortical control in our primate ancestors. Adding some laryngeal phonation, as occurs in an infrequent macaque call termed a girney, would be enough to render these visual signals audible. A second evolutionary step would have been the development of our unique cortical–brainstem connections[9], giving us increased control over the larynx. These may have evolved to more effectively exploit the acoustic bandwidth offered by the rapidly oscillating vocal tract, yielding the speech signal we know today.

Although speech is just one facet of language, and not necessarily even the most important one, its neural and evolutionary basis is becoming increasingly well understood. These new results suggest that the evolutionary history of speech and other aspects of language may have been full of odd turns and surprises. ■

W. Tecumseh Fitch *is in the Department of Cognitive Biology, University of Vienna, 1010 Vienna, Austria.*
e-mail: tecumseh.fitch@univie.ac.at

1. Ghazanfar, A. A., Morrill, R. J. & Kayser, C. *Proc. Natl Acad. Sci. USA* **110,** 1959–1963 (2013).
2. Drullman, R., Festen, J. M. & Plomp, R. *J. Acoust. Soc. Am.* **95,** 2670–2680 (1994).
3. Smith, Z. M., Delgutte, B. & Oxenham, A. J. *Nature* **416,** 87–90 (2002).
4. Fitch, W. T. *The Evolution of Language* (Cambridge Univ. Press, 2010).
5. MacNeilage, P. F. *Behav. Brain Sci.* **21,** 499–511 (1998).
6. Ghazanfar, A. A., Takahashi, D. Y., Mathur, N. & Fitch, W. T. *Curr. Biol.* **22,** 1176–1182 (2012).
7. Logothetis, N. K., Pauls, J., Augath, M., Trinath, T. & Oeltermann, A. *Nature* **412,** 150–157 (2001).
8. Rilling, J. K. *et al. Nature Neurosci.* **11,** 426–428 (2008).
9. Jürgens, U., Kirzinger, A. & von Cramon, D. Y. *Cortex* **18,** 125–139 (1982).

ENVIRONMENTAL SCIENCE

The shape of nitrogen to come

An analysis reveals the huge impact of human activity on the nitrogen cycle in China. With global use of Earth's resources rising per head, the findings call for a re-evaluation of the consumption patterns of developed societies. SEE LETTER P.459

MARK A. SUTTON & ALBERT BLEEKER

Although Earth's atmosphere consists of nearly 80% dinitrogen (nitrogen gas, N_2), most living organisms cannot use this form of the element and require it to be converted into usable forms, such as ammonia. Humans have long exploited the ability of leguminous crops to fix dinitrogen into usable reactive nitrogen compounds, improving soil fertility. But the amount of reactive nitrogen produced in this way is now greatly exceeded by that produced industrially[1]. Together with nitrogen oxides, another form of reactive nitrogen produced as a by-product of combustion processes, nitrogen compounds released into the environment by human activity are weaving a web of unforeseen consequences. On page 459 of this issue, Liu *et al.*[2] quantify the massive scale of these changes to the nitrogen cycle across China, which are a direct result of increases in human activities such as food production, travel and energy consumption*.

In a study remarkable for the scale of its achievement, Liu *et al.* have shown how increases in the rate of the release to the atmosphere of nitrogen oxides (NO_x) and ammonia (NH_3) have been matched by increases in the amounts of atmospheric reactive nitrogen (N_r) deposition, measured in precipitation. To do this, they drew on more than 300 published data sets of N_r deposition from across China spanning 30 years (from 1980 to 2010). Most importantly, the authors went on to show how nitrogen uptake by plants and its levels in leaves have changed across China as a consequence.

The focus of the study was to provide quantified evidence of biogeochemical and biological change, but Liu and colleagues' results can also be considered as indicators of a pan-dimensional modification to the nitrogen cycle. The components of this modification include: the formation of

---

*This article and the paper under discussion[2] were published online on 20 February 2013.