

are limitations to Reufer and colleagues' laser, however. In particular, the amount of current that could be passed through the device is limited for several reasons: silver contacts are not ideal for injecting charge effectively into semiconducting polymers; the thicker polymer film used in this set-up makes charge injection and transport more difficult; and the electrical conductivity of the thin indium–tin oxide film is relatively poor, limiting the area of such lasers and increasing their operating voltage. Overall, however, Reufer and colleagues' results<sup>1</sup> bring low-cost, battery-operated, visible lasers a step closer, and will stimulate renewed interest in plastic lasers. ■

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## Neurobiology

# Why voles stick together

Evan Balaban

The tendency for animals to form social bonds after sexual activity varies greatly from species to species. Work with voles illuminates a molecular pathway in the brain that influences such differences.

A report on page 754 of this issue continues a fascinating line of inquiry into the basic brain mechanisms that contribute to social behaviour. There, Lim and colleagues<sup>1</sup> show that increasing the expression of a single protein in a particular brain region of male meadow voles makes them more socially cohesive — rather like their close relation the prairie vole.

There is much that researchers would like to know about the social behaviour of animals (including ourselves, as discussed on page 705 of this issue<sup>2</sup>). What, for instance, are the brain mechanisms that mediate the formation of bonds between individuals? How do these mechanisms change within and between populations and species over evolutionary time? The humble vole has provided a wonderful opportunity to pursue these issues.

There are many species of vole, and they exhibit markedly different patterns of social attachment. For instance, male prairie voles in captivity are likely to form preferential associations with one female, defined by close physical contact, choosing to spend more time with her when given equal access to several females, and keeping other males away from her<sup>3</sup>. These preferential associations form most readily after sexual activity. Captive male prairie voles also tend to interact with and care for their young. (Both traits vary in degree among wild populations<sup>4</sup>.) Captive males of the closely related meadow vole, by contrast, exhibit weaker 'pair-bonding' with females (again, this is variable in the wild<sup>5</sup>), and give little attention to young.

Studies of the social organization, behavioural ecology and hormones of voles<sup>6,7</sup> have

linked such differences in 'affiliative behaviour' to variation in the expression patterns of the receptors for two related signalling molecules, oxytocin and arginine vasopressin (vasopressin for short)<sup>3</sup>. These molecules are released in the brain after sex, and are also involved in other reproduction-related behaviours and in unrelated functions such as water retention and stress.

Notably, the vasopressin 1a receptor (V1aR) is expressed in greater numbers in the ventral pallidum region of the forebrain in male prairie voles than in male meadow voles<sup>8</sup>. Although the exact relationships of the ventral pallidum to other brain regions and to behaviour are still unclear, the neighbouring nucleus accumbens is part of the brain's 'reward system', which signals that a particular behaviour is worth doing again. In prairie voles, manipulation either of signals mediated by the neurotransmitter dopamine in the nucleus accumbens<sup>9</sup>, or of vasopressin signalling within (at least in part) the ventral pallidum<sup>10,11</sup>, can substitute for or block the effects of sexual activity on preferential association — showing the importance of both regions in forming attachments. The expression of dopamine receptors shows little natural variation between species, however, hinting that the key to the differing behaviour of prairie and meadow voles might lie in the variation in vasopressin receptors.

Lim *et al.*<sup>1</sup> now take us beyond correlations in the study of these receptors, by experimentally manipulating the expression of V1aR. The authors wanted to find out whether adult male meadow voles that have prairie-vole-like expression of

vasopressin receptors also show prairie-vole-like social behaviour. They discovered that, as a group, male meadow voles that have more V1aRs in the ventral pallidum spend more time both with their mates and near juveniles than do controls. (They do not, however, engage in paternal care (consistent with previous suggestions that these traits can be dissociated in prairie voles<sup>3</sup>). Lim *et al.* also show that, as in prairie voles, preferential association in the experimentally manipulated meadow voles is prevented by prior blockage of dopamine receptors. A similar study of adult male prairie voles with above-average V1aR levels<sup>12</sup> found a potentiation of preferential association with females, and increased time spent in proximity to unfamiliar juveniles.

So Lim *et al.* argue that, in male prairie voles, the sexually induced release of vasopressin triggers its receptors in the ventral pallidum, which somehow enable the intrinsically rewarding sensations experienced after copulation to become reliably associated with the individual features of a particular female, such as her odour. (It is unclear whether vasopressin signalling simply causes familiar animals to spend more time close to one another, allowing the association with the rewarding effects of sex to occur more reliably, or whether it directly causes changes in the inputs to, or function of, the brain reward systems.) Male meadow voles, by contrast, form weaker social bonds because of a lower level of signalling in the relevant brain region. But because the subsequent molecular and neuronal circuitry is highly similar in these species, changing the expression of this one receptor can profoundly alter the circuit's function — implying that evolutionary selection can act on this single molecule to produce major changes in social behaviour.

If the V1aRs are indeed the adjustable nozzle atop a social-glue dispenser in the mammalian brain, these results could have wider significance for understanding social behaviour — and some of its dysfunctions, as seen, for instance, in autism — in humans and animals. Caution is warranted on three fronts, however. First, several studies<sup>4,13,14</sup> indicate that changes in V1aR expression alone might not fully account for naturally observed differences in pair-bond formation in voles. Individuals from populations and species with similar V1aR levels but different behaviour will be valuable in the search for other molecular and cellular components of the social glue.

Second, vasopressin signalling mediates many other reproductively related and unrelated functions. So the experimental change in the meadow-vole ventral pallidum might detrimentally affect other brain functions in manipulated individuals — unless they have additional, compensatory genetic modifications, as prairie voles evidently do.

An understanding of the wider evolutionary significance of this manipulation must await a fuller documentation of its physiological consequences.

Finally, it has been suggested<sup>11,3,15</sup> that variation in the expression of the V1aR gene, and hence evolutionary changes in vole social behaviour, can be attributed solely to variation in the gene's regulatory DNA sequences. But perhaps we should not be so quick to leap to this conclusion. For instance, mice engineered to include a prairie-vole V1aR gene (plus control sequences) fail to display prairie-vole-like levels of V1aR expression in the ventral pallidum<sup>16</sup>. Similarly, control sequences from the prairie-vole V1aR gene do not yield higher expression levels in rat brain cell lines than do such sequences from montane voles (which are similar to meadow voles)<sup>15</sup>. Gene variation in signalling or regulatory molecules that interact with the V1aR control region are also likely to be important.

Understanding the role of genetic variation in the evolution of any trait requires knowledge of the major genes involved, their distribution among individuals, the distribution of genetically defined individuals in different environments, and the dependence of the trait on the environment for each individual and at each stage of development. This is a tall order, especially for behavioural characteristics. But the research on voles

gives us hope that classical comparative studies of natural populations, judiciously coupled with modern molecular and cellular neurobiology, will continue to provide insights into the relationships between genes, brain-cell collectives, ecology and chance in social behaviour. ■

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science. For example, if entangled particles were distributed throughout various sectors of a quantum computer, then quantum teleportation could provide a means for distant quantum bits (or qubits) to interact without the requirement of physical proximity — effectively ‘quantum wiring’, with desirable scaling properties. In addition, disposable quantum software could be delivered from a remote location using a generalized form of quantum teleportation to enhance the capabilities of rudimentary quantum hardware<sup>7</sup>.

Remarkably, the two groups<sup>5,6</sup> have used quite different techniques for achieving teleportation, and yet both reach very similar values of so-called fidelity. Fidelity is a figure of merit that quantifies how well the quantum state that appears in the second ion after teleportation resembles the original quantum state; fidelity is 1 in the ideal case. Both teams report values around 0.75, which exceeds the ‘classical’ value of 2/3 that can be reached without quantum entanglement. For classical teleportation, the original quantum state is simply measured, and a new quantum state recreated by using only the classical information obtained from the measurement.

Both experiments have thereby reached the milestone of unconditional, or deterministic, teleportation of atomic qubits. The initial quantum state is prepared on demand, then teleported from one ion to another with high efficiency at the push of a button (which in fact triggers a computer-controlled array of complex operations). The teleported state is then available for further experiments. Such bona fide teleportation of quantum bits, following the original proposal of Bennett *et al.*<sup>1</sup>, has not been achieved before — not in experiments with polarization states of light, and certainly not for any material system. The only other setting in which deterministic teleportation has been realized is that of continuous quantum variables (roughly, the amplitude and phase of a beam of light)<sup>4</sup>.

In terms of the actual physical systems, Riebe *et al.*<sup>5</sup> employ ground and metastable states of trapped calcium ions as qubits; Barrett *et al.*<sup>6</sup> utilize two ground states in the hyperfine structure of beryllium ions. As for the implementation of quantum operations, the two experiments differ in several important aspects. First, crucial elements of both teleportation and quantum computing are joint operations for two qubits that cannot be performed by simply manipulating the qubits separately. Such two-body interactions are required for the creation of entanglement between two ions (step 1 in Fig. 1), and for the implementation of joint or Bell-state measurements (step 3). Riebe *et al.* use a version of the Cirac–Zoller two-qubit gate<sup>8</sup>, which relies on the common centre-of-mass motion of the ions. Barrett

Quantum physics

# Push-button teleportation

H. J. Kimble and S. J. van Enk

Two groups have succeeded in teleporting quantum states between different atoms — a spectacular advance in the quest to achieve quantum computation.

In 1993, Charles Bennett and colleagues described a remarkable protocol for transporting a quantum state from one location to another<sup>1</sup>, a protocol that succeeds even when the quantum state is completely unknown at the respective sites. Such quantum teleportation makes use of an extraordinary quantum resource, namely entanglement between two systems. Moreover, it also requires ordinary classical information obtained by performing a joint measurement on the system that carries the quantum state to be teleported and one component of the entangled state (as outlined in Fig. 1). Strangely, neither classical nor quantum channels individually carry any information about the quantum state, leading to the characterization of teleportation as the disembodied transport of quantum states. Initial experimental demonstrations of quantum teleportation, from 1997 onwards, involved the quantum states of beams of light<sup>2–4</sup>. Now, in a

landmark advance, two teams have achieved teleportation for the quantum states of massive particles<sup>5,6</sup>.

As described on pages 734 and 737 of this issue, Riebe *et al.*<sup>5</sup> and Barrett *et al.*<sup>6</sup> have generated coherent superpositions of two internal states for a single trapped ion (P in Fig. 1), and have teleported these quantum states to a second ion (B), with the help of a third, auxiliary ion (A). The import of these experiments goes well beyond the demonstration of teleportation *per se*, because both schemes incorporate many complex procedures that are required for scalable quantum computing. Indeed, the ion-trap set-up is generally considered one of the most promising implementations for quantum computing, as is once again confirmed by these experiments.

Moreover, quantum teleportation has emerged as an essential operation for diverse tasks in quantum information