

the dark energy thought to be driving the accelerating expansion of the Universe? Yes and no. These sub-luminous SNe Ia are too dim to be seen at great distances, so are not useful in cosmological studies. However, one of the great worries about the use of SNe Ia, especially given their murky origins, is how their average properties may change with cosmic time¹¹. Therefore, any understanding of their progenitors is progress. The dream is to one day understand what causes each subclass of SN Ia, so that we can model any change in supernova demographics as we look back in time through the Universe. Better yet, a separation

of SNe Ia into different categories, arising from physically distinct processes, may make each subclass better standard candles.

Pakmor and colleagues' study is a big step forwards: after decades of modelling, it finally seems that white-dwarf mergers can make some supernovae. But it is an early step down a long path exploring where this scenario might take us. And if it can't explain all SNe Ia, what are the rest? ■

D. Andrew Howell is at the Las Cumbres Observatory Global Telescope Network and the Department of Physics, University of California, Santa Barbara, California 93117, USA.

e-mail: ahowell@lco.gn.net

1. Hoyle, F. & Fowler, W. A. *Astrophys. J.* **132**, 565–590 (1960).
2. Whelan, J. & Iben, I. *Astrophys. J.* **186**, 1007–1014 (1973).
3. Iben, I. & Tutukov, A. V. *Astrophys. J. Suppl.* **54**, 335–372 (1984).
4. Leonard, D. C. *Astrophys. J.* **670**, 1275–1282 (2007).
5. Saio, H. & Nomoto, K. *Astron. Astrophys.* **150**, L21–L23 (1985).
6. Pakmor, R. *et al. Nature* **463**, 61–64 (2010).
7. Taubenberger, S. *et al. Mon. Not. R. Astron. Soc.* **385**, 75–96 (2008).
8. Howell, D. A. *et al. Astrophys. J.* **556**, 302–321 (2001).
9. Howell, D. A. *et al. Nature* **443**, 308–311 (2006).
10. Gallagher, J. S. *et al. Astrophys. J.* **685**, 752–766 (2008).
11. Sullivan, M. *et al. Astrophys. J.* **693**, L76–L80 (2009).

NEUROSCIENCE

Editing out fear

Gregory J. Quirk and Mohammed R. Milad

Retrieving a memory initiates a window of vulnerability for that memory. Simple behavioural methods can modify distressing memories during this window, eliminating fear reactions to traumatic reminders.

We all have memories that we would rather forget, some embarrassing and some painful. Most of us learn to cope with these memories, but this can be difficult for those suffering from post-traumatic stress disorder (PTSD), in which reminders of traumatic events can trigger dread and fear. One way to counteract such associations is to extinguish them with repeated exposures to traumatic reminders within a safe environment. However, because this extinction process does not eliminate the fear memory, fear reactions often return, especially during stress.

An alternative approach to treating PTSD was suggested by studies¹ in rodents. These studies showed that the mere retrieval of a memory triggers a reconsolidation process, during which the memory briefly becomes labile before being re-stored. Drugs that block reconsolidation can degrade the original fear memory in animals, but it has been difficult to apply such a strategy to humans because most of these drugs are toxic. On page 49 of this issue, Schiller *et al.*² report that giving extinction training to humans during the reconsolidation window effectively redefines fearful memories as safe*.

It has been known for a century that memories must undergo a consolidation process in order to be stored in the long term³. An exciting and more recent discovery was that retrieving a memory triggers a reconsolidation process that employs many of the molecular mechanisms used in the original consolidation. Reconsolidation has been observed for several types of memory across different species⁴, but these studies beg the question “what is the advantage

*This article and the paper under discussion were published online on 9 December 2009.

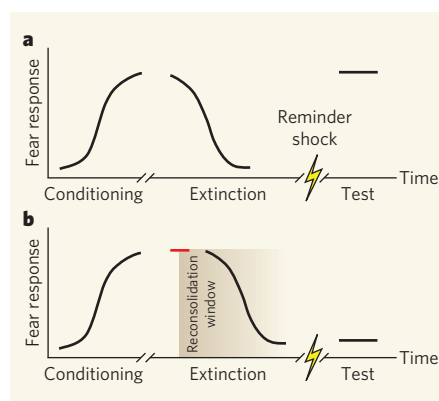


Figure 1 | Preventing fear's return. **a**, Schiller *et al.*² conditioned human volunteers to fear a visual cue paired with a mild electric shock. They then extinguished the fear using extinction training, in which the cue was repeatedly presented in the absence of the shock. Fear responses extinguished in this way returned the following day when the participants were given a reminder shock. The graph shows the magnitude of a participant's fear response during the three parts of the experiment. **b**, Volunteers who received extinction training shortly after a retrieval trial (red line), which causes the subject to recall the fear memory, exhibited no fear response after being given a reminder shock the next day. This is because the retrieval of a memory triggers a reconsolidation window during which the memory can be updated by extinction training.

of remaking a memory multiple times?” One possibility is that reconsolidation allows memories to be updated in the light of events that have occurred since the last retrieval⁵.

This hypothesis was recently tested⁶ by some of the authors of the present study. In rats

conditioned to fear a tone paired with an electric shock, the researchers observed that extinction training conducted within 10 minutes of memory retrieval eliminated fear of the tone, and prevented the fear from returning under a variety of circumstances, even if a reminder shock was administered. Furthermore, rats in which fear memories had been extinguished within this critical window were resistant to re-learning the tone–shock association. So, instead of forming a new memory of safety, extinction training given during the updating window apparently converted the existing memory⁶ of fear into one of safety.

These findings⁶ in rodents raised questions about human memory. Does the retrieval of fear memories in humans trigger similar updating windows in which the memories could be modified by extinction training? If so, then how specific and long lasting are the memory-editing effects of reconsolidation–extinction procedures? To find out, Schiller *et al.*² used a well established fear-conditioning protocol, in which human volunteers learned that the appearance of a visual cue (a blue square) predicts a shock to the wrist (Fig. 1). The authors used the participants' skin conductance as a measure of their fear — skin conductance increases with sweating, a phenomenon exploited by lie detectors.

As in rodents, humans who recalled their fear memory 10 minutes before extinction training showed no fear response when tested 24 hours later. Furthermore, their fear responses did not return even if they were given a reminder shock at the start of the test day — they reacted to the blue square as if it had never been associated with a shock. By contrast, those participants whose memories were extinguished outside the critical window exhibited high fear responses when tested 24 hours later.

So are the memory-editing effects of extinction specific to the reactivated memory, or do they generalize to other memories? To address this issue, Schiller *et al.* conditioned volunteers to fear two stimuli, a blue square and an orange square, but only reactivated the fear memory of the blue square in a reminder trial. The participants underwent extinction training for both stimuli and were then administered

a shock. This caused a return of their fear only in response to the orange square, confirming that the memory-editing effect of the reconsolidation–extinction procedure was specific to the reactivated memory.

Finally, to investigate the longevity of the effect, the authors brought a sample of their volunteers back to the lab one year later, and gave them a reminder shock. Remarkably, those who had received extinction training within 10 minutes of the reminder trial the year before continued to be immune to the shock. Taken together, Schiller and colleagues' results thus show that updating windows exist in humans, that the effects of extinction training during this window are stimulus-specific, and that the effects last for an extended period not commonly observed for other experiments in this field.

Schiller *et al.* studied healthy volunteers, but an exciting possibility is that their findings might be useful for the treatment of anxiety disorders such as PTSD. Current therapies involve extinction-based exposure to memory cues, but because extinction training is less effective in PTSD⁷, pharmacological methods

are being explored to augment fear extinction⁸, or to block fear reconsolidation^{9,10}. The obvious advantage of Schiller and colleagues' reconsolidation–extinction method is that no drugs are required, only a modification of the timing of standard exposure therapy.

There are, however, several issues that need to be carefully examined with regard to the potential clinical efficacy of this approach². The aversive stimulus used in the study was a mild electric shock, which might have quite distinct effects from the kind of life-threatening events that lead to PTSD. Furthermore, it is not clear whether Schiller and colleagues' method would be effective for modifying fear memories acquired months or years before extinction training, rather than in the 24-hour period of their experiments. Finally, PTSD is a complex disorder that involves symptoms such as avoidance of traumatic reminders, emotional numbing, nightmares, flashbacks and sleep disturbances. The extent to which all these symptoms depend on aversive associations that are susceptible to editing remains to be determined. Nevertheless, Schiller and colleagues' findings are an exciting development

that paves the way for mechanistic studies, in both rodents and humans, to discover how memory retrieval prepares fear circuits for updating by extinction training. ■

Gregory J. Quirk is in the Department of Psychiatry, University of Puerto Rico School of Medicine, San Juan, Puerto Rico 00936-5067, USA. Mohammed R. Milad is in the Department of Psychiatry, Massachusetts General Hospital, Harvard Medical School, Charlestown, Massachusetts 02129, USA.
e-mails: gquirk@yahoo.com;
milad@nmr.mgh.harvard.edu

1. Nader, K. M., Schafe, G. E. & LeDoux, J. E. *Nature* **406**, 722–726 (2000).
2. Schiller, D. *et al.* *Nature* **463**, 49–53 (2010).
3. McGaugh, J. L. *Science* **287**, 248–251 (2000).
4. Nader, K. & Hardt, O. *Nature Rev. Neurosci.* **10**, 224–234 (2009).
5. Alberini, C. M. *Trends Neurosci.* **28**, 51–56 (2005).
6. Monfils, M.-H., Cowansage, K. K., Klann, E. & LeDoux, J. E. *Science* **324**, 951–955 (2009).
7. Milad, M. R. *et al.* *Biol. Psychiatry* **66**, 1075–1082 (2009).
8. Davis, M., Ressler, K., Rothbaum, B. O. & Richardson, R. *Biol. Psychiatry* **60**, 369–375 (2006).
9. Brunet, A. *et al.* *J. Psychiatr. Res.* **42**, 503–506 (2008).
10. Kindt, M., Soeter, M. & Vervliet, B. *Nature Neurosci.* **12**, 256–258 (2009).

QUANTUM PHYSICS

Trapped ion set to quiver

Christof Wunderlich

The peculiar ultra-fast trembling motion of a free electron — the Zitterbewegung predicted by Erwin Schrödinger in 1930 when he scrutinized the Dirac equation — has been simulated using a single trapped ion.

In seeking to investigate the properties of a particular system, natural scientists often encounter situations in which the difficulty in accessing and tuning the system of interest experimentally prevents such investigation being made. An effective, and widely used, remedy for these unfortunate instances is the numerical simulation of the system's properties and behaviour on a computer. However, in many cases, faithful digital replication of the system is not possible because of limitations in computing power and memory. These limitations become prohibitive for systems governed by the laws of quantum mechanics, not least for many-body quantum systems, because the range of possible system states grows exponentially with the number of system constituents.

In such cases, new insight may be provided by a quantum simulation, which simulates a quantum system using a different, experimentally accessible and controllable quantum system. On page 68 of this issue, Gerritsma *et al.*¹ report their use of a single atomic ion trapped in an electrodynamic cage to simulate a free particle (for instance, an electron) in an extremely fast quivering motion superimposed

on a slow drift — the Zitterbewegung, as it is known, which was first predicted by Erwin Schrödinger in 1930 but has so far not been directly accessible to experiments.

In the late 1920s, Paul Dirac succeeded in devising an equation — the Dirac equation — that married two descriptions of the physical world, each of which had already revolutionized our view of it: quantum mechanics and special relativity. This equation describes the quantum-mechanical behaviour of half-integer-spin particles, taking into account the fundamental principles of special relativity — for example, that the speed of light in a vacuum is the ultimate speed limit at which information can be transferred across distances in the Universe.

Non-relativistic quantum mechanics predicts phenomena that are difficult to reconcile with our classical perception of the world. For example, quantum-mechanical superposition states, in which a particle simultaneously occupies separate regions of space, are hard to envisage, but cleverly designed wave-interference experiments reveal that such unexpected behaviour is possible. Adding special relativity to the mix results in even more perplexing

phenomena. In interpreting the solutions of his relativistic quantum-mechanical equation, Dirac postulated the existence of an anti-particle to the electron — the positron. Although initially seen as a daring prediction, positrons were observed shortly thereafter, and today are routinely used for medical imaging.

Other predictions of the Dirac equation have remained elusive, particularly Schrödinger's Zitterbewegung, which arises from the interference of particle states that are interpreted to have positive and negative energies. This is a prediction of the Dirac equation that describes a 'free' particle — that is, one that is not subject to external forces and yet changes its velocity, in blatant conflict with Isaac Newton's second law of motion in classical mechanics.

The 'art' of a quantum simulation lies in the faithful reproduction of the Hamiltonian (a mathematical entity from which the system's static and dynamic properties can be derived) of the quantum system we want to learn about using a system we can experiment with^{2–4}. The experiment performed by Gerritsma *et al.*¹ was designed such that each quantity appearing in the Hamiltonian of a trapped ion mirrors a quantity in the Hamiltonian of a free relativistic quantum particle (a free Dirac particle, for instance an electron). Two of the ion's internal energy states represent positive- and negative-energy states of a free Dirac particle; and the position and momentum of the trapped ion simulate the position and momentum of the free Dirac particle. To reproduce the (one-dimensional) Dirac Hamiltonian, the authors irradiate the ion with laser light, which allows the ion's motion in one dimension to be coupled to the two internal energy states.