distinct, indicating separate introduction events into each continent[5].

Many aerial *Phytophthora* pathogens, including *P. infestans*, have a narrow host range. By contrast, *P. ramorum* exhibits a remarkably broad range, at least in its new invasive behaviour[4,5]. Outside nurseries, it has infected more than 40 species across 12 families of tree and non-tree hosts in California, and another 40 species in Europe, although only a minority of tree species have proved highly susceptible. The mechanisms underlying this wide host potential are not known, but their importance is highlighted by another development.

In September 2009, widespread dieback and mortality of mature and juvenile Japanese larch, *Larix kaempferi*, were observed in plantations across southwest England and shown to be associated with infection by *P. ramorum*[7,8]. Symptoms include needle necrosis, branch dieback, stem lesions and heavy resin bleeding. This is the first serious damage caused by *P. ramorum* to conifers and plantation trees. When growing adjacent to larch, other species such as beech, chestnut, birch, rhododendron and Douglas fir are being infected, indicating heavy infection pressure consistent with observations of exceptionally high *P. ramorum* spore counts on artificially inoculated larch needles[7] and frequent infection of larch needle litter.

Between May and July 2010, further outbreaks were detected by aerial and ground surveys in south Wales[8] and southern England (Fig. 1). An estimated 1,900 hectares of larch plantations (about 0.5 million trees) now show symptoms of *P. ramorum* infection: in other words, the fungus is spreading on a landscape scale in Britain, as in the United States. The British Forestry Commission and the private sector are felling all affected trees to minimize further spread, both to forests and to susceptible heathland vegetation.

Larch is not only an important timber tree in western Britain, but is also the only deciduous conifer, providing value for landscape, biodiversity and recreational purposes. This development could therefore have a significant impact on local economies and Britain's strategic reserve of timber. Moreover, *P. ramorum* and the other invasive pathogens now entering Europe could narrow the choice of plantation species for reafforestation, especially in Britain[9], and undermine proposals to use tree planting as a means of mitigating climate change through carbon sequestration[9].

The jump of *P. ramorum* from rhododendron to larch illustrates its behavioural unpredictability. Another issue of concern is its longer-term ecological and evolutionary potential. Introduced pathogens inevitably encounter new hosts (some with little intrinsic resistance) and other novel biotic and abiotic influences. These represent selection forces that, individually or collectively, will result in adaptation. Some recently invasive tree pathogens have also exchanged genes with resident species, resulting in a genetically modified pathogen or even an entirely new pathogen[10]. One example is *Ophiostoma novo-ulmi*, which is responsible for the pandemic of Dutch elm disease and which has acquired 'useful' genes from a related species during its migration[11]. Another is *Phytophthora alni*, which is attacking alder across Europe and is a species hybrid that may have arisen in a European nursery[10]. Each invasive pathogen therefore represents an uncontrolled, open-ended experiment in evolution[2].

It remains to be seen whether *P. ramorum* has already begun to adapt to larch and what other hosts it will attack in the future. It has yet to be found outside Europe and North America, but may represent a threat to trees in climatically suitable habitats in South America, the Himalayas, Asia and Australasia, including *L. kaempferi* in its native Japan. Given current international trade practices and biosecurity protocols, and the considerable epidemic momentum that *P. ramorum* now has in the United States and Britain, prospects for preventing its further spread do not look good. ■

C. BRASIER, FOREST RES.; B. WYLDER, FORESTRY COMM.

Figure 1 | Consequences of infection with *Phytophthora ramorum*. Left, dead and dying tanoak in California, July 2010. Right, similarly afflicted larch in southwest England, May 2010.

Clive Brasier and Joan Webber are at Forest Research, Alice Holt Lodge, Farnham, Surrey GU10 4LH, UK.
e-mail: clive.brasier@forestry.gsi.gov.uk

1. Jones, D. R. & Baker, R. H. A. *Plant Pathol.* **56,** 891–910 (2007).
2. Brasier, C. M. *Plant Pathol.* **57,** 792–808 (2008).
3. Hawksworth, D. L. *Mycol. Res.* **105,** 1422–1432 (2001).
4. Rizzo, D. M., Garbelotto, M. & Hansen, E. M. *Annu. Rev. Phytopathol.* **43,** 309–335 (2005).
5. Grünwald, N. J., Goss, E. M. & Press, C. M. *Mol. Plant Pathol.* **6,** 729–740 (2008).
6. Werres, S. *et al. Mycol. Res.* **105,** 1166–1175 (2001).
7. Webber, J. F., Mullet, M. & Brasier, C. M. *Plant Pathol. New Dis. Rep.* (in the press).
8. British Forestry Commission (www.forestry.gov.uk) News releases: 13077 (17 November 2009); 13492 (8 April 2010); 13677 (10 June 2010); 13819 (16 July 2010).
9. Read, D. J. *et al.* (eds) *Combating Climate Change — A Role for UK Forests* (The Stationery Office, Edinburgh, 2009).
10. Brasier, C. *Nature* **405,** 134–135 (2000).
11. Paoletti, M., Buck, K. W. & Brasier, C. M. *Mol. Ecol.* **15,** 249–262 (2006).

HIGH-TEMPERATURE SUPERCONDUCTIVITY

The benefit of fractal dirt

Jan Zaanen

Measurements of X-ray diffraction on small patches of a copper oxide superconductor reveal that oxygen crystal defects form fractal structures that seem to promote high-temperature superconductivity.

In the area of electronic materials, 'oxides' is a buzzword[1] referring to chemically complex solids containing oxygen and transition metals. In these materials, electrons can team up at low temperatures to display collective behaviour that is much richer than that found in conventional metals and semiconductors. The realization of this behaviour started with the discovery of superconductivity at a high temperature in copper oxides in 1986. These 'high-T_c cuprates' (T_c is the temperature below which the material superconducts) are still king of the hill in the oxide landscape, because the myriad of mysterious 'quantum matter' phenomena observed in these systems is among the most intriguing puzzles in modern physics[2].

Conventional semiconductors took off when materials scientists had learned how to grow crystals that are nearly perfect. For the oxides, this is a formidable challenge. Besides the need to control the many elements in the unit cell of the material's crystal lattice, the chemistry is further complicated by oxygen's reputation as the vagabond among the elements. It tends to roam around as an 'oxygen interstitial' in the skeleton formed by

NATURE|Vol 466|12 August 2010

50 & 100 YEARS AGO

50 YEARS AGO

The problem of the 'Abominable Snowmen' is discussed by S. V. Obruchev ... beginning with Waddell's report of 1898 about the hairy wild man called 'Yeti' by the Tibetans. In the Soviet Press during 1957–59 there appeared a number of articles on this subject, especially on the possible presence of the 'Snowman' in the Pamirs. In 1958 a special expedition sent to the Pamirs to study this problem reported negatively ... At the same time, numerous recent finds of teeth of a huge anthropoid ape—*Gigantopithecus*—in China suggest that the Tibetan 'Yeti' and the legendary 'Snowman' of the Pamirs and Mongolia may all refer to the former, or present-day but rare, presence of this type of ape in the high-altitude regions of the Himalayas and the Pamirs.

From *Nature* 13 August 1960.

100 YEARS AGO

'Wild plants on waste land in London' — The waste ground between Aldwych and the Strand has been colonised by a variety of plants, most of which show luxuriant growth. Many of the colonists have fruits or seeds adapted to wind distribution, as in the case of the winged fruit of the sorrel (*Rumex acetosa*), and of the plumed seeds of the hairy willow herb (*Epilobium hirsutum*) and French willow, or rose bay (*E. angustifolium*), by far the most conspicuous plant on the ground. It is of interest that *E. angustifolium*, which is absent in many of the waste places of London, occurs in the garden of Fountain Court, near the Strand ... A probable auxiliary exists in the sparrow, through the alimentary canal of which various seeds and fruits no doubt pass, and it is not unlikely that others become attached to its feet by means of the sticky London mud. It will be remembered that Darwin in the "Origin of Species" describes eighty-two plants as springing from the feet of a single partridge ... The above list is by no means exhaustive.

From *Nature* 11 August 1910.

other elements, freezing in random positions when the samples are cooled. Fratini *et al.*[3] report on page 841 a direct observation, using a novel synchrotron-light microdiffraction technique, of how this 'oxygen dirt' is structured on the micrometre scale in the La_2CuO_{4+y} superconductor.

The result turns out to be surprisingly beautiful: the oxygen interstitials form geometrical patterns that look the same on different scales, ranging from a micrometre up to fractions of a millimetre. Although such fractals are ubiquitous elsewhere in nature, it comes as a complete surprise that crystal defects can accomplish this feat. Even more stunningly, Fratini *et al.* demonstrate that this fractal organization directly promotes the superconductivity: T_c increases when the fractality is more complete. This finding hints at a possible relation with the mysterious quantum-matter side of high-T_c superconductors: the 'quantum-critical' property of the cuprate electrons, referring now to a scale invariance that governs the quantum physics[4].

The experiment of Fratini *et al.* is conceptually straightforward, but it needs the big machines installed at synchrotrons: it amounts to measuring X-ray diffraction on micrometre-sized patches of the sample and combining the results into real-space maps. Zooming in on the diffraction peaks associated with an ordering of the oxygen interstitials in a nanometre-scale 'superlattice' (see Fig. 1c of the paper on page 841), they find that this superlattice order varies considerably in space. Both its magnitude and spatial distributions show power-law behaviour (Fig. 2 on page 842) — the unique fingerprint of scale invariance. This fractal-defect structure is astonishing, and there is nothing in the textbooks even hinting at an explanation.

An obvious alley to explore is dynamical-systems theory, a subject offering insights into fractal phenomena as diverse as the shapes of fern leaves, the 'fat tails' of option pricing in the financial markets and the Gutenberg–Richter earthquake law[5]. The focus in those cases is on the way that things evolve over time, but where is this motive in the case of oxygen interstitials? The fractal patterns actually originate in a rapid quench of the sample from a high temperature, at which the oxygen atoms are highly mobile, to liquid-nitrogen temperature. I suspect that some novel form of 'turbulence' is responsible and is at work when the oxygen 'liquid' formed in the crystal freezes out rapidly.

To demonstrate that the quality of fractal organization promotes the superconductivity, the authors[3] prepared, using different quenching protocols, two samples of La_2CuO_{4+y} that are similar except for the scale at which the fractality comes to an end — 400 or 180 micrometres, respectively. Accordingly, they find that the superconductor deteriorates, from a muscular form at $T_c = 40$ kelvin, to a messy, inhomogeneous one at $T_c = 32$ kelvin. This is hard to comprehend given the conventional understanding of superconductivity. The transition to a superconducting state is driven by the binding of electrons in pairs, and the length scales of relevance for this process (pair size and electronic mean free path) are supposed to be on the nanometre scale. Why should the pairing mechanism be sensitive to subtle changes in the crystalline disorder happening on a length scale that is more than a factor of 1,000 larger?

Is this a sign of the strangeness of the cuprate electron matter? In conventional metals and superconductors, the electrons form a weakly interacting quantum gas, and they go, in the first instance, their own way. But not so in high-T_c superconductors, in which the electrons form poorly understood, highly collective quantum states[2]. The few things that we condensed-matter physicists know about these systems follow from phenomenological analysis of experimental information. A highlight in this regard is that, in superconductors such as those studied by Fratini *et al.*, one finds fingerprints of scale invariance in measurements of the materials' electronic behaviour but in a quantum-physical incarnation[4]. In this 'quantum-critical state', the electrons form collective patterns that look the same regardless of scale. However, this fractal trait is now present on scales both in space and in time, because the electrons are in a state of perpetual quantum motion[6,7].

Could there be some profound relation between the static scale invariance in the defect structure and this quantum criticality, explaining why superconductivity is so sensitive to the former? All along, the problem faced by condensed-matter physicists has been the lack of a general mathematical theory capable of describing quantum-critical metals. But, very recently, help has arrived from an unexpected side. It turns out that the 'anti-de-Sitter space/conformal field theory correspondence', a mathematical highlight of string theory, is encoding the physics of states that look remarkably like the cuprate metals in — *nota bene* — the properties of special black holes[8]. This theory insists that quantum-critical metals have a destiny that they cannot escape: they have to turn into superconductors[9,10]. Hence, quantum criticality is good for superconductivity, but it could of course be that quantum criticality itself is disrupted by crystalline disorder. It is, however, a speciality of things that are scale invariant that they care less about influences that by themselves are also scale invariant. In this sense, the fractal defect structure could be good news, eventually even for superconductivity. But does this quantum-criticality hypothesis explain the sensitivity of superconductivity to changes occurring in the oxygen dirt on fractions of a millimetre? Even the strange worlds described by string theory might not be strange enough to explain this remarkable fact, which will undoubtedly inspire exciting future research. ■

Jan Zaanen is at the Instituut Lorentz for Theoretical Physics, Leiden University, PO Box 9506, 2300 RA Leiden, the Netherlands.
e-mail: jan@lorentz.leidenuniv.nl

1. 'Materials for electronics' spec. sect. *Science* **327,** 1595–1611 (2010).
2. Editorial *Nature Phys.* **2,** 133 (2006).
3. Fratini, M. *et al. Nature* **466,** 841–844 (2010).
4. Zaanen, J. *Nature* **430,** 512–513 (2004).

5. http://en.wikipedia.org/wiki/Chaos_theory
6. Sachdev, S. *Quantum Phase Transitions* (Cambridge Univ. Press, 1999).
7. Varma, C. M., Nussinov, Z. & van Saarloos, W. *Phys. Rep.* **361,** 267–417 (2002).
8. Faulkner, T., Iqbal, N., Liu, H., McGreevy, J. & Vegh, D. *Science* doi:10.1126/science.1189134 (2010).
9. Zaanen, J. *Nature* **462,** 15 (2009).
10. Hartman, T. & Hartnoll, S.A. Preprint at http://arxiv.org/abs/1003.1918 (2010).

BEHAVIOURAL NEUROSCIENCE

Genes and the anxious brain

Andreas Meyer-Lindenberg

Some people are naturally more anxious than others. A brain-imaging study in monkeys provides surprising insights into which brain regions are under the influence of genes in this phenomenon and which are not.

How anxiously we react to threat or adversity is part of our personality. This stable characteristic is called trait anxiety, and those with high trait anxiety are more prone to mental disorders such as depression, substance abuse and psychosis[1]. Trait anxiety is heritable, with genes explaining much of the variability between individuals[2]. In this issue, Oler *et al.*[3] investigate genetic effects on the activity of brain regions that mediate trait anxiety (page 864).

The subjects of this study were rhesus monkeys — 238 from several generations of a single-family pedigree — at an average age corresponding to that of humans just before puberty. The authors exposed the animals to a human intruder, a validated social-threat procedure that reveals an anxiety trait. They found, by examining both blood levels of the stress hormone cortisol and behaviours such as 'freezing', that some monkeys reacted with high anxiety, and others with less.

Concurrently, Oler *et al.* measured metabolic activity in the brain by injecting the monkeys with ^{18}FDG, a radioactive analogue of glucose that is taken up and trapped in nerve cells according to their activity at the time of exposure to the social threat. The authors then anaesthetized the monkeys in order to image, using positron emission tomography, a 'snapshot' of regional brain metabolism during the preceding stress procedure.

The results indicate that, in anxious monkeys, brain activity is higher in a variety of areas, but most prominently in two key signalling structures for negative emotion, the amygdala and the anterior hippocampus. Activity in these two structures explained a sizeable proportion of the variance in anxiety behaviour from monkey to monkey (Fig. 1).

Much research in anxiety has focused on the amygdala[4], which signals environmental danger and triggers 'fight-or-flight' responses. But extensive evidence also links the anterior hippocampus — an essential structure for 'declarative' memory — to anxious behaviour and trait anxiety[4]. Furthermore, there are strong interactions between the amygdala and hippocampus, which mediate emotional memory.

What proportion of anxiety-related activity in the brain of monkeys is genetic? In their well-characterized pedigree, Oler *et al.* could precisely estimate genetic similarity between any two monkeys. They thus mapped heritability (the proportion of variability that can be attributed to genes) across the brain. Surprisingly, they found that activity in the anterior hippocampus was under strong genetic influence, but observed no significant heritability in the amygdala (Fig. 1). Given the importance of these two structures for trait anxiety, and their close functional connection, this pronounced difference is unexpected.

Do these findings mean that the amygdala is no longer to be considered part of the neurogenetic pathway for trait anxiety? Not necessarily. The amygdala is a structure that shows bursts of activity and can be fickle where imaging is concerned. Furthermore, Oler *et al.* investigated the brain of each animal only once — during the stress condition. They may, therefore, not have been able to fully characterize the proportion of neural activity that was truly due to stress. For this, a control condition during which animals are not stressed is needed.

Previous studies in monkeys[5] and humans[6] that involved a control condition have, in fact, revealed effects of gene variants on the amygdala. Moreover, genetic mechanisms do not just play out in regional brain activity, but also shape the neural networks in which these regions participate. In particular, interactions between the amygdala and another brain region, the prefrontal cortex, may be highly relevant to the effect of genetic variation on trait anxiety[7], because the resulting circuit regulates the activity of the amygdala during the processing of negative emotion. In addition, interactions between the hippocampus and the amygdala have been linked to aspects of personality[8]. To characterize these circuits, other techniques such as functional magnetic resonance imaging must be used, because measuring interactions between different regions requires repeatedly imaging them over time.

If Oler and colleagues' data can be confirmed in humans, research on the neurogenetic basis of anxiety and psychiatric disorders should focus more on the hippocampus than it has so far. Changes in hippocampal size and function have been reported[9] in depression and anxiety disorders, but have often been considered a consequence of stress-related hormonal changes. This paper[3] suggests that hippocampal processing of threat and stress signals could also be on the causal pathway that links genetic risk to disease manifestation: genes affect personality through their effect on hippocampal threat processing, which therefore becomes an intermediate, or 'endo', phenotype.

Indeed, genetic variants that have been identified through genome-wide association studies of mental illnesses such as bipolar disorder or schizophrenia modulate hippocampal activity[10]. With the knowledge that hippocampal activity is a heritable component of the neural network mediating trait anxiety, this activity can itself be used in genome-wide association studies to discover gene variants affecting the hippocampus. This approach deserves particular attention because drugs that target the products of these genes, and the hippocampus, could be a new entry point into the treatment of mental disorders. Oler and co-workers' paper[3] could, therefore, not only change thinking about

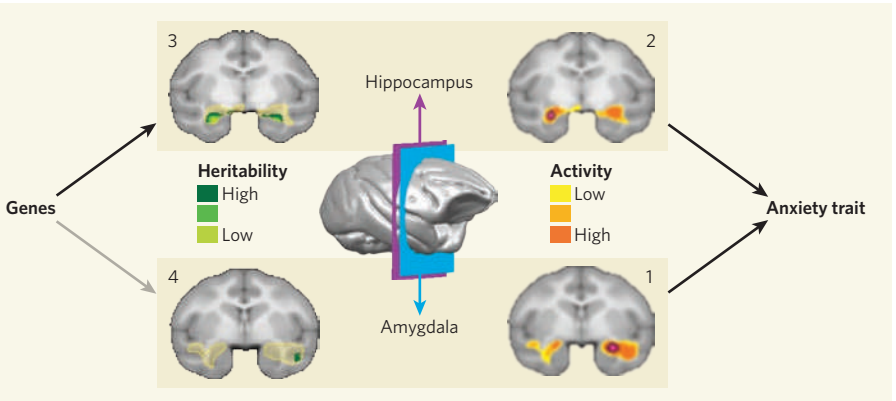

Figure 1 | When anxiety runs in a family of primates. Oler *et al.*[3] exposed monkeys to a social threat and then measured ^{18}FDG distribution in their brains as an indicator of metabolic activity there. They show that both the amygdala (scanned brain slice 1) and the hippocampus (2) mediate variations in trait anxiety. However, the authors find that only hippocampal activity (3), and not amygdalar activity (4), is explained by genetic relatedness. (Brain images from ref. 3.)