Theorists calculate that this drastic change in the structure of matter sets in over a narrow range of temperatures centred around 10^{12} K. To gauge the change, it is instructive to compare the degrees of freedom — the number of different particles that energy can go to. On the hadronic side of the transition, the important particles at these temperatures are just the pions (the other hadrons being too heavy). These are spinless particles and come in three types — with positive, negative or zero electric charge. On the quark–gluon side, there are three colours of quarks of three different types (up, down and strange — the other quarks are too massive to play a part) and each has two possible spin directions. Taking into account antiquarks, we find $3 \times 3 \times 2 \times 2 = 36$ quark degrees of freedom. In addition, there are eight gluons each with two possible spin directions — thus 54 degrees of freedom altogether, compared with the previous three. A direct consequence is that a given input of energy will raise the temperature of a quark–gluon plasma much less than it would the hadronic gas, as the energy has to be shared by many more particles.

Despite the dramatic nature of these predicted changes, it is not easy to establish experimentally that one has produced a quark–gluon plasma. Difficulties arise because the number of particles reaching the detectors after a heavy ion collision is extremely large, and because the plasma, even if produced, has only a fleeting existence in a very small region.

The experimenters are like inspectors who must examine the residue of a great explosion to determine if it was due to conventional or nuclear weapons (or perhaps a meteorite). Ambitious responses to this challenge are being mounted at CERN and at Brookhaven, where the heavy-ion accelerator RHIC will come into operation next summer.

Already, CERN has seen what might be the first harbinger of the quark–gluon plasma. Charm–quark/charm–antiquark pairs, making up the J/ψ family of particles, seem to find it much more difficult to stay paired once the energy in a fireball exceeds a threshold value (Fig. 2c). This certainly suggests the deconfinement mentioned above. It has been advocated for some time as a signature of the quark–gluon plasma. Even though the issue is muddied by the fact that the J/ψ particles will be buffeted more at higher temperature whether one has hadrons or quark–gluon plasma, nevertheless the apparent sharpness of the threshold, and other details, point towards the plasma. What makes the latest results[3] especially intriguing is that they are the first that sceptical theorists[7] have not been able to explain without invoking a quark–gluon plasma.

A big question left open by these experiments is whether the transition from normal matter to quark–gluon plasma, as a function of temperature, is continuous or truly abrupt. If it is abrupt (in the language of phase transitions, first order), superheating and supercooling are possible, and could trigger explosive instabilities. If such events occurred in the early Universe, they must have appreciably perturbed its evolution.

We anticipate other relics of the quark–gluon plasma created in accelerators. An especially intriguing possibility is that the quark–antiquark condensate which normally fills space could reassemble incorrectly, forming a domain analogous to domains in magnets. When such a domain snaps back into place, it will release a laser-like pion beam[8].

More prosaically, it would be reassuring to see the predicted high specific heat, and the associated increase in multiplicity of particles. In particular, strange quarks and antiquarks are much lighter and therefore much easier to produce than the K mesons in which they are normally confined. So events following the creation of a quark–gluon plasma should be especially strange, in more ways than one. □

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1. Abreu, M. C. *et al. Phys. Lett. B* **410,** 327–343 (1997).
2. Satz, H. preprint hep-ph/9711289 on xxx.lanl.gov
3. Gonin, M. http://www.cern.ch/NA50/papers/bnl.ps
4. Wilczek, F. *Annu. Rev. Nucl. Sci.* **32,** 177–209 (1982).
5. Schmelling, M. preprint hep-ex/971002 on xxx.lanl.gov
6. Burrows, P. preprint hep-ex/9705013 on xxx.lanl.gov
7. Gavin, S. & Vogt, R. *Phys. Rev. Lett.* **78,** 1006–1009 (1997).
8. Rajagopal, K. in *Quark–Gluon Plasma* 2 (ed. Hwa, R.) 484–554 (World Scientific, Singapore, 1995).
9. http://www.cern.ch/Opal/events/qq.gif & http://www.cern.ch/Opal/events/qqg_lego.gif
10. http://www.cern.ch/NA50

Neurobiology

Phantoms of the brain

Jon H. Kaas

The brain often reorganizes itself after damage to some of its sensory inputs, so that neurons that were responsive to the missing inputs come to respond to remaining inputs[1]. After the loss of somatosensory input from the hand, for example, the region of the somatosensory cortex on the opposite side of the brain that is normally responsive to touch on the hand becomes responsive, over months of recovery, to touch on the face or arm[2–6].

When the brain reorganizes in this way, do the newly reactivated neurons signal that the sensations are coming from the location of the stimulated skin, or do they signal instead the location of their original but missing source of activation? This question has been tackled by Karen Davis and colleagues (page 385 of this issue[7]) by recording and stimulating brain responses with microelectrodes placed in the somatosensory thalamus of patients with missing limbs (Fig. 1, overleaf).

People with amputations often have the feeling that the missing limb is still present as a so-called phantom limb[8]. Furthermore, sensations on the missing limb can sometimes be evoked by touching 'trigger zones' on other parts of the body. For example, touching the face or remaining upper arm on the side of an arm amputee may produce sensations both of those body parts and of the missing hand[9,10]. A logical interpretation of these trigger zones is that touching the arm or the face activates neurons in the arm or the face territories in the brain, and the territories normally devoted to the hand.

According to this view, this type of brain reorganization is not beneficial, but instead contributes to the misperception that something is touching the phantom hand. Another possibility, however, is that the reactivated neurons devoted to a missing hand or foot become recalibrated by experience so that they come to signal stimuli on remaining body parts such as the hand or face. This, of course, would not explain trigger zones, but it would mean that the extensive brain reorganization that follows amputation is potentially useful.

People without amputations report appropriately localized sensations when sensory representations in the brain are stimulated electrically[11]. As part of a therapeutic procedure for amputees with pain, Davis and co-workers[7] placed microelectrodes in normal parts of the somatosensory thalamus and in that part of the thalamus where neurons previously would have been activated by stimulating the missing limb. The investigators determined the regions of skin where light touch activated neurons recorded at various electrode locations, thereby defining the receptive fields of those neurons; and they electrically stimulated the same or nearby neurons to produce sensations, thus defining sensation fields.

In the normal, undeprived portions of the somatosensory thalamus, neurons had matching receptive fields and sensation fields. But in some amputees, those with notable phantom sensations, stimulating neurons with receptive fields on the stump of the missing limb produced sensations referred to the missing limb (Fig. 1). Thus, the brain had reorganized so that the territory of the missing limb in the thalamus had become responsive to the sensory inputs from the stump of the arm, whereas the activation of neurons in this territory continued to signal sensations on the missing limb.

This does not tell us how or where the sensations are generated, because the activated

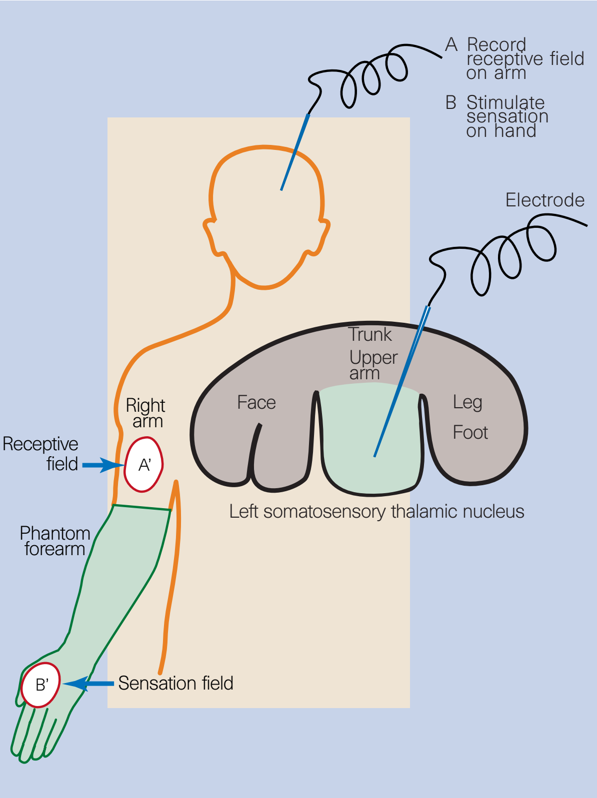

Figure 1 **Evidence of brain reorganization without respecification. The studies of Davis *et al.*[7], discussed here, involved recording and electrically stimulating neurons in the somatosensory thalamus of patients with a missing forearm or lower leg (not shown). When the electrode is inserted into the portion of the somatosensory thalamus where neurons are normally activated by touch on the hand, recordings (A) reveal receptive fields on the stump of the amputated limb (A′ on the right arm). Thus, the thalamus has reorganized so that the hand region responds to the upper arm. When the same neurons are electrically stimulated (B), sensations are felt on the missing hand (sensation field, B′). So the reorganized hand portion of the thalamus continues to signal the hand's existence.**

neurons in the thalamus in turn activate neurons elsewhere in the brain. But we now know that, for at least some people, deprived but reactivated neurons do not take on new and appropriate functions. Instead, these neurons continue to carry out their original roles. However, mismatched receptive and sensation fields were not found in all patients, suggesting that sometimes the reactivated neurons recalibrated to signal stump locations rather than locations on the missing limb.

The results of Davis and co-workers are consistent with limited observations of Woolsey *et al.*[12] on the effects of stimulating somatosensory cortex in a patient with phantom leg pain. Electrical stimulation of the leg area of somatosensory cortex produced the sensations in the phantom leg. No studies were carried out on the possible reorganization of this cortex, but the observation that sensations were referred to the phantom leg indicates that that part of the cortex continued to signal the existence of the missing leg. We can conclude from these studies that neurons in the brain can retain their original functions long after they have had time to adopt new ones.

The thalamic stimulations and recordings in amputees provide support for another important conclusion. Most of the evidence for brain reorganization after injury or altered experience has come from studies of the more accessible sensory representations of the cortex on the surface of the brain. Information from receptors in the skin is relayed through sensory nerves to the lower brain stem, then to the thalamus, and next to the cortex. Depending on the circumstances of injury or experience, reorganizations of cortical maps could depend on modifications of neural circuitry that occur in the cortex, subcortical stations, or both. In monkeys with long-standing therapeutic forelimb amputation, the hand region of cortex is activated by intact inputs from the upper arm and face[3]. In these same monkeys, nerve fibres from the upper arm appear to have sprouted in the lower brain stem to innervate neurons normally contacted by nerve fibres from the missing hand.

From this it seems that the growth of new nerve terminals at the level of the first relay station activates the deprived brain-stem neurons, which project to and activate deprived neurons of the somatosensory thalamus, which in turn relay to the cortex. The extensive reactivation of deprived portions of the human thalamus demonstrates that there is a subcortical locus for much of the reorganization that follows limb amputation. □

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1. Kaas, J. H. *Annu. Rev. Neurosci.* **14,** 137–167 (1991).
2. Pons, T. P. *et al. Science* **252,** 1857–1860 (1991).
3. Florence, S. L. & Kaas, J. H. *J. Neurosci.* **15,** 8083–8095 (1995).
4. Yang, T. T. *et al. Nature* **368,** 592–593 (1994).
5. Flor, H. *et al. Nature* **375,** 482–484 (1995).
6. Jain, N., Catania, K. C. & Kaas, J. H. *Nature* **386,** 495–498 (1997).
7. Davis, K. D. *et al. Nature* **391,** 385–387 (1998).
8. Melzack, M. *Trends Neurosci.* **13,** 88–92 (1990).
9. Ramachandran, V. S., Rogers-Ramachandran, D. & Stewart, M. *Science* **258,** 1159–1160 (1992).
10. Ramachandran, V. S., Rogers-Ramachandran, D. & Cobb, S. *Nature* **377,** 489–490 (1995).
11. Penfield, W. & Boldrey, E. *Brain* **60,** 389–443 (1937).
12. Woolsey, C. N., Erickson, T. C. & Gilson, W. E. *J. Neurosurg.* **5,** 476–506 (1979).

NATURE

100 YEARS AGO

"Rev. C. L. Dodgson" – A formidable champion of Euclidean methods in the elementary teaching of geometry has just passed away after a short illness. … Without stint of labour he submitted to rigid logical analysis every text-book on the subject that came to his notice, undismayed by their surprising number, the result being the amusing and, at the same time, deep "Euclid and his Modern Rivals," published in 1879, in which he demonstrated the logical superiority of Euclid's method over all the others examined. … He invented a new method of evaluating determinants, which is published in the *Proceedings* of the Royal Society for 1866, and also a method (which was published in NATURE) of easily determining the day of the week corresponding to any date. In October last he described in NATURE a brief method of dividing a given number by 9 or 11; and a second paper on the same subject, which appears in our correspondence columns this week, probably represents his latest contribution to mathematics. … Mr. Dodgson's mind was essentially logical, in spite of the whimsical humour which has endeared "Lewis Carroll" to every boy and girl – nay, every adult – in the kingdom. A shy and retiring man, he was to his friends a most charming companion, overflowing with the quaintest of humour, and one whose love for children was typical of himself, and whom to know was to love.

From *Nature* 20 January 1898.

50 YEARS AGO

The Royal Society Empire Scientific Conference held in June 1946 considered and approved a resolution advocating that where scientific papers or text-books are expressed primarily in British units, provision should be made for the inclusion of metric equivalents or conversion factors. … Sir Charles Darwin in opening the meeting emphasized that the matter to be discussed was one of intelligibility only, and had nothing to do with the introduction of the metric system in Britain. By making it possible for the foreigner to convert British units immediately into metric, publishers of scientific papers and books would assist Britain to attain the position of the centre of science in Europe.

From *Nature* 24 January 1948.