A light and a dark side

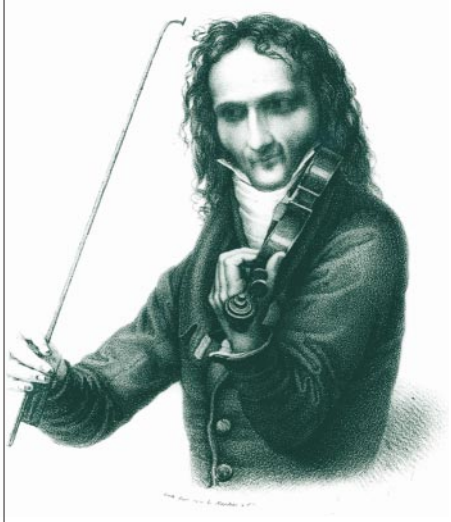
Cortical reorganization

"The brain's representations of the periphery are dynamic and continuously modified by experience."

Thomas Elbert and Sabine Heim

The gigantic network that makes up the human cerebral cortex is dynamically and unceasingly reorganizing itself. This continuously changing entity is not easy to track, but we can glimpse the living brain by observing the organization within zones representing the first stages of sensory input from the outside world. Primary auditory, visual and somatosensory cortices mirror the spatial arrangement of the respective peripheral receptors: tonal frequency (place in the cochlea), visual space (place on the retina) or body surface are represented in the form of maps imprinted on the cortical sheet.

Although genetically encoded programs control the connections of these maps from the periphery to the cortical destination, their organization ultimately depends on the efficacy of the synapses connecting the nerve cells comprising the network, which is affected by environmental experience. For instance, two receptors of the same fingertip are more frequently activated in sync than are two receptors of different digits. According to the hebbian learning model, synchronous stimulation would lead to connections between the representations of the same fingertip but to a separation from those of the other digits: representational zones are shaped by the temporal pattern of coincident experience. An alteration in behaviourally relevant input towards the cortex will trigger a reorganization — alteration — of the map. The representation of a fingertip, for instance, can be enlarged; representations of adjacent fingers can invade its territory; or the representation of two fingers can become fused.



Cortical representation in musicians, such as Niccolò Paganini, reflects their art.

Musicians provided one of the first examples of this phenomenon in humans: string players usually practise for hours a day over many years. While playing, the digits of the left hand are continuously fingering the strings, but the right-hand task of manipulating the bow involves much less processing of information from individual fingers. In string players, the cortical representations of the somatosensory left-hand regions were found to be expanded compared with those of the right hand and compared with the left hand of non-musicians.

What holds for the somatosensory cortex also holds for auditory processing: larger responses are elicited in the auditory cortex when musicians hear their own instrument played than are elicited by tones from other instruments. Perceptual correlates of map alteration indicate superior performance — one 'bright side' of cortical plasticity.

The most remarkable alteration of cortical maps has been observed in amputees. The nonstimulated area — for instance the arm region — remains actively engaged in information processing of nearby zones. As a consequence, the adjacent face and shoulder areas invade what was formerly arm territory. There is a close association between this invasion and adverse symptoms such as phantom-limb pain and, in the auditory system, tinnitus. Because treatment designed to reverse this invasion reduces phantom-limb pain, the adverse response is probably an unwanted consequence of the dynamic brain. This maladaptive disaster reveals the dark side of cortical reorganization.

The functional organization of one level of the cortex is governed by the interplay of earlier and later representational stages of the sensory processing stream. In mammals, the thalamus (one of the highest processing stages of the reptilian brain) feeds sensory information into the cortex. The cortex in turn feeds processed information back to the thalamus. When these top-down projections are inactivated, thalamic functional organization is dramatically degraded. There are nearly ten times as many fibres projecting top-down from the representational cortex to the thalamus as there are bottom-up from the thalamus to the cortex. Through this route, top-down processing determines the way in which sensory information is organized, filtered and processed. What we perceive is not only a matter of the incoming event but also a highly edited configuration of top-down organization and reorganization.

It is not surprising, then, that lesions in the central nervous system can lead to alterations in functional organization at all processing levels. After a brain lesion there are initial deficits in behaviour, perceptual or cognitive skills, but often spontaneous relief of symptoms. Cortical reorganization may be crucial for such recovery. New intervention strategies in conditions such as hemiplegia, writer's cramp, phantom-limb pain, aphasia or language-based learning disorders provide a 'bright side' ready to be exploited by neurorehabilitation.

The dark side occurs when a peripheral lesion, by itself manageable, is triggered by an unusually intense, stressful experience to cause a negative or catastrophic cortical reorganization, such as that underlying phantom-limb pain and tinnitus. Fusion of representational zones is at the core of dystonia (such as musician's cramp or writer's cramp); Michael Merzenich's notion that dyslexia and even autism may be a consequence of inadequate functional organization (of the phonemotopic representation) stirs an exciting new avenue of research. And what about extreme experiences, such as traumatic stress or childhood abuse? Do they have the power to trigger reorganization of maps beyond the representational cortex, with consequent secondary disasters?

In a nonlinear, dynamic, self-organizing system such as the brain, small causes can have large effects. The brain should not be studied just in terms of monocausal genetic and environmental influences. Learning is the adaptation of brain dynamics — when it has been disastrous, behavioural techniques (in conjunction with appropriate medication) may be the remedy. This prospect is the bright side of the dark side. ■

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FURTHER READING

Buonomano, D. V. & Merzenich, M. M. *Annu. Rev. Neurosci.* **21,** 149–186 (1998).
Gilbert, C. D. *Physiol. Rev.* **78,** 467–485 (1998).
van Praag, H., Kempermann, G. & Gage, F. H. *Nature Rev. Neurosci.* **1,** 191–198 (2000).
Elbert, T., Heim, S. & Rockstroh, B. Neural plasticity and development. In *Handbook of Developmental Cognitive Neuroscience.* (eds Nelson, C. & Luciana, M.) (MIT Press, Cambridge, MA, 2001).
Nudo, R. J. *Curr. Opin. Neurobiol.* **9,** 740–747 (1999).